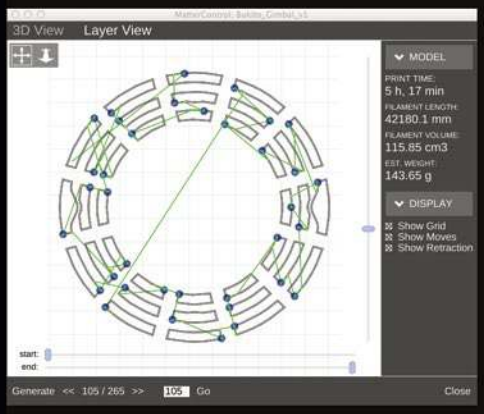
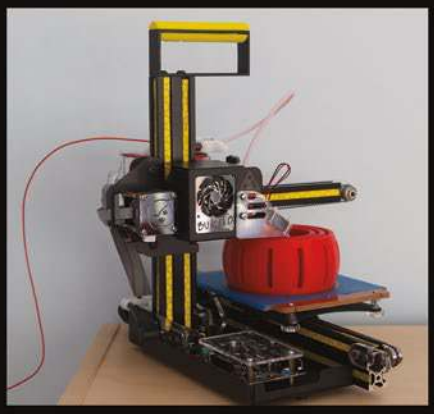
TECHNOLOGY IN ACTION™

Mastering 3D Printing

MODELING, PRINTING, AND PROTOTYPING WITH REPRAP-STYLE 3D PRINTERS





Joan Horvath

Deezmaker 3D PRINTERS

www.it-ebooks.info

For your convenience Apress has placed some of the front matter material after the index. Please use the Bookmarks and Contents at a Glance links to access them.

Apress®

www.it-ebooks.info

Contents at a Glance

About the Author xvii

About the Technical Reviewer xix

Acknowledgments xxi

Introduction xxiii

Part 1: Open Source 3D Printers 1

Chapter 1: A Brief History of 3D Printing 3

Chapter 2: The Desktop 3D Printer 11

Chapter 3: Open Source 21

Part 2: The 3D Printing Process 31

Chapter 4: Making a 3D Model 33

Chapter 5: Slicing a 3D Model 47

Chapter 6: Driving Your Printer: G-code 65

Chapter 7: Material Considerations 77

Chapter 8: Case Studies 89

Part 3: 3D Printing Meets Traditional Prototyping 111

Chapter 9: Moving to Metal 113

Chapter 10: Large Prints and Post-Processing 129

Chapter 11: Troubleshooting 137

www.it-ebooks.info

Part 4: Using Your Printer 149

Chapter 12: Printers in the Classroom 151

Chapter 13: Scientific Visualization 165

Chapter 14: Futures 175

Appendix A: Typical Printer Settings 183

Appendix B: Links and Resources 189

Index 193

www.it-ebooks.info

Introduction

3D printers have been around for about 30 years, but you would never know that from the current explosion in both 3D printers and the uses for them. Although some of the more extreme hype in the field will go away in due course, 3D printing really does enable some new ways of thinking about creating products, particularly custom ones. What is new is the availability of low-cost 3D printers (costing from a few hundred to a few thousand dollars). These lower-cost machines have the promise of making the front of the product-development process much more efficient and enabling distributed manufacturing. This book focuses on these consumer-level printers and their applications. In particular, the emphasis is on open source 3D printers—machines whose software and hardware designs are freely shared online.

3D printing can be defined pretty simply: creating an object by building it up layer by layer, rather than machining it away, the way you would by making something from a block of wood, or squirting something into a mold, as you would for injection-molded plastic parts. Its flexibility and the sheer magic of seeing something built from nothing have captured people's imaginations, and it is clear that surprising applications will continue to pop up for years to come.

This book is intended for several audiences. First, it is meant to be a self-contained tutorial on consumer 3D printers and the open source software that runs them. The field is changing very rapidly, though, and as such you should expect that the details of the software and hardware will shift away from the book's descriptions. A recurring metaphor you will see in this book is that 3D printing is about as complex as cooking. In cooking terms, you will find that this book has a bias that shies away from providing recipes to follow exactly and instead leans toward teaching you how to cook over the long haul.

This book also is intended to be used as a text for a semester-length class or university extension certificate series covering 3D printing, its applications, and its place in manufacturing innovation. It might be paired with an in-depth class on 3D computer-aided design (CAD) software for students interested in engineering and industrial or product design applications. Similarly, it might be paired with in-depth instruction in one of the sculptural 3D-modeling programs for students developing skills in 3D animation or fine art.

Part 1 (Chapters 1–3) of the book gives background on the history of these printers, talks about how the hardware works, and gives some insight into the open source and do-it-yourself movements that nurtured the propagation of the consumer 3D-printer industry. Part 2 (Chapters 4–8) is the nitty-gritty tutorial on the workflow of using a 3D printer: developing a 3D model, slicing it into layers that the printer will create one at a time, and controlling the printer in real time. Part 2 also reviews available materials and walks through some case studies. Part 3 reviews how you can take your 3D print and post-process it to improve the surface finish, create larger projects, or even cast a metal part from your printed one. Part 3 covers troubleshooting, too, just in case you got a little too ambitious for your printer's linking . Finally, in Part 4 you will read about how educators, scientists, and others are using 3D printers, and where the field may go in the future.

If you are just starting your exploration of the field, welcome. Hopefully, this book will be a good guide for you, and you will finish it ready to take on challenges and try to help build this new frontier along with us.

www.it-ebooks.info

PART 1

Open Source 3D Printers

The first part of this book introduces you to open source 3D printers. A user makes a number of tradeoffs choosing an open source, "hackable" design, and these tradeoffs and the design rationale behind them are the focus of the first three chapters.

Chapter 1 is a brief history of 3D printing, with a focus on consumer printing. Chapter 2 talks about how these printers work and why there is a sudden blooming of interest in the technology. Chapter 3 rounds out this section with a discussion of the open source philosphy and the pros and cons of being a part of an open source 3D-printer community.

www.it-ebooks.info

CHAPTER 1

A Brief History of 3D Printing

Enormous hype surrounds 3D printing, with predictions that it will spur a manufacturing renaissance in the United States (and perhaps the world), with everyone suddenly able to run their own cottage manufacturing facility. There are many areas where 3D printing really is creating significant change, particularly in designing and prototyping new products, in the arts, and in visualizing abstract concepts.

However, 3D printing is still a rather complex undertaking, and most users are still very much in the early adopter stage. In this book we try to make 3D printing as simple as we can, while still giving you enough of the "ifs, ands, and buts" to allow you to create sophisticated projects.

This chapter walks you through a brief history of 3D printing, with a focus on the open source consumer 3D printer technologies. In Chapter 2, we dive into the details of how consumer-level 3D printing works. Then, in Chapter 3, we talk about the open source software environment and culture, and how the field moves forward.

What Is 3D Printing?

3D printing is conceptually straightforward. An object is created by starting with nothing and adding material a layer at a time until you have a completed object. There are many natural examples of the process, and lower-tech variations have been used by other names for millennia—for example, making a brick wall.

The current 3D printing boom is really just an evolution and convergence of technologies and techniques that have been around for a while. However, there are some crucial technical and business-environment innovations covered in this chapter that came together to make consumer 3D printing affordable. To give a clear mental picture of how 3D printing works, we start with natural processes that look a lot like it.

Nature's 3D Printers

3D printing seems like an advanced technology, but many organisms have been doing the equivalent for eons. Some of nature's many 3D printers include the mollusks that give us seashells (Figure 1-1). As they get bigger, mollusks start adding calcium carbonate to their outer shell, which gives the growing animal more room inside. If you look carefully at seashells, you will see lines of growth.

www.it-ebooks.info

Figure 1-1. *Seashells are a product of natural "3D printing"*

As it gets longer and wider the shell gets thicker, too, so that it does not become fragile. The shell is secreted and condensed out of materials in the creature's environment instead of laid down with a nozzle like the printers you will read about in this book, but the results can still be pretty remarkable. For more details, see www.scientificamerican.com/article/how-are-seashells-created/.

Similarly, many rock formations in the southwestern United States were laid down when ancient oceans built up layers of silt. The resulting sandstone has since been carved away by wind, rain, and plant roots. Figure 1-2 is an example of the final result of the processes that first build up material one layer at a time and then erode some of it away.

Figure 1-2. *Another example of natural 3D printing in Cave Valley, Zion National Park. Photo courtesy of Niles Ritter*

www.it-ebooks.info

When people watch a natural process (like the ones resulting in the shells in Figure 1-1 or the sandstone in Figure 1-2), a few might have been inspired to create a fabrication process that will work the same way. Next, let's look at some traditional manufacturing processes that foreshadowed 3D printing.

Historical Additive Manufacturing

3D printing is a form of *additive manufacturing*. Additive manufacturing starts with nothing and builds up parts by laying up material on some sort of build platform. A lot of conventional manufacturing is *subtractive,* meaning that you start with a block of material (like metal or wood) and start cutting away material until you have the part that you want plus a pile of sawdust or metal shavings. The rock formation in Figure 1-2, as we noted, was a bit of both.

Some types of additive manufacturing have been around for a long time. A very simple example is the humble brick wall. A brick wall is built up one brick at a time, with the addition of a bit of mortar, based on either a formal plan drawn by an architect or engineer, or perhaps just built out of a contractor's head, if the job is routine enough. All the steps you will see in 3D printing are there in building a brick wall: designing a desired end product, planning out how to arrange the layers so that the structure will not fall down while it is being built, and then executing the product one layer at a time. 3D printers add the elements of robotic control to this process of building an object up a layer at a time.

Types of 3D Printers

Conceptually, 3D printers work similarly to making a brick wall (although they are a lot more flexible in what you can build). One way or another, 3D printers start with a computer model of an object and then use that model to control a robotic device that uses one of three technologies to lay up an object. Broadly speaking, there are three categories of additive manufacturing: selective binding, selective solidification, and selective deposition. Typically, people refer to these technologies by the acronyms SLS, SLA, and DLP, as discussed in this section. We are defining these three categories here to keep the sheer number of technologies understandable and to organize them a little.

Selective binding technologies make a 3D printed object from a powder (metal and gypsum are common materials) by applying binding agents or heat to fuse the powder's particles together. An example is SLS (selective laser sintering) in which a laser is used to fuse one layer of powdered material at a time. The first layer is fused to a platform, and then another thin layer of powder is added above the first, and so on as the model is built up. The powder acts as a supporting medium for the print, so that very complex and delicate prints can be created. The fine powder can be hard to deal with, though, and the printers tend to be expensive.

Selective solidification makes a solid object from a vat of liquid by selectively applying energy to solidify the liquid a layer at a time. Again, typically a first layer is created on some sort of build platform, which then moves down into the liquid (or, in some cases, a build platform pulls up out of the liquid). One example is stereolithography (SLA), which uses UV light to solidify a resin with a laser, or sometimes a digital light projection (DLP) imager, to harden a whole layer at a time. Either way, the model often needs to be cured afterwards, and the resin can be messy to deal with. Desktop SLA printers are starting to come onto the market now but are more expensive than the filament-based printers described next.

Selective deposition techniques only place material where you want it. The filament-based printers we focus on in this book work this way, by melting a filament and then placing the melted plastic to create an object precisely. There are also 3D printers that inkjet-print liquid resin, which then is UV cured. Printers that use a powder mixed with a binder are arguably a hybrid of selective binding and selective deposition.

Which technology makes the most sense for you to use depends on several things: your budget, the model's complexity, and the finest detail that is necessary. By and large, cheaper technologies produce less-detailed results, although all the technologies are evolving rapidly. This book focuses on the lower-cost end of the spectrum: printers that melt a filament and then deposit the material. The other technologies typically are not appropriate for the average home user because of cost and materials-handling issues, although this may change over time in this rapidly evolving field.

www.it-ebooks.info

■ **Tip** If you need high resolution for your final project, you might choose to have a consumer printer at home to develop prototypes and iterate a design. You can then send a print to a *service bureau* to be printed on an expensive machine for you elsewhere and then shipped.

The term *3D printing* is actually a bit misleading because people tend to think of their 2D inkjet consumer printers and make extrapolations that are not really accurate. In reality, a 3D printer is a small robot factory. You start the manufacturing process, and (with luck!) a part emerges after a while without any human intervention. However, there are many steps involved in preparing that print; you are not just "clicking Print." Those steps and associated design decisions are the focus of Chapters 4 through 7.

The rest of this book will primarily focus on consumer-level printers that melt plastics and then extrude the plastic a layer at a time. The next section briefly reviews the evolution of these printers over the last 30 years or so. To distinguish the printers developed over the last 30 years from the more general additive manufacturing, we will use the term *robotic 3D printers*. This is not commonly used terminology, however, and after the next section we will simply call them *3D printers*, assuming the clams (and bricklayers) of the world will not object to being excluded.

■ **Tip** This chapter reviews the history and technologies of 3D printing very briefly. If you want more detail, Christopher Barnatt's book *3D Printing: The Next Industrial Revolution* (CreateSpace, 2013—available from www.explainingthefuture.com) contains good reviews of the various technologies, their histories, and how they work.

The Early Days of Robotic 3D Printers

Charles W. (Chuck) Hull is generally credited with developing the first working robotic 3D printer in 1984, which was commercialized by 3D Systems in 1989. These machines were SLA systems (described earlier in this chapter), and many large commercial machines still use this technology. Other early work was taking place at the Massachusetts Institute of Technology (MIT) and University of Texas.

A flurry of patents followed in the early 1990s for various power-based systems. These systems squirt a binder very precisely on the surface of a vat of powder to create layers (again, with a downward-moving platform). Alternatively, a laser can be used to fuse the powder together (in SLS, as explained earlier in this chapter). SLS patents became the basis for Z Corp, another early printer company that created large industrial printers. Z Corp is now part of 3D Systems.

Meanwhile, S. Scott and Lisa Crump patented fused deposition modeling (FDM) in 1989 and co-founded the printer manufacturer Stratasys, Ltd. This technology (more generically called FFF, for fused filament fabrication) feeds a plastic filament into a heated extruder and then precisely lays down the material. When key patents expired in 2005, this technology became the basis of the RepRap movement described in the next section.

There are 3D printing technologies that can print at the molecular level (called *two-photon polymerization*, which uses femtosecond pulsed lasers to fuse a powder). These are documented mostly in scientific literature at the moment. At the other extreme, it is possible to print large concrete structures (*contour crafting,* developed at University of Southern California and described at www.contourcrafting.org). Researchers are printing food and even human organs. Chapter 14 covers more advanced technologies.

The pace of development in the field is very rapid; new methodologies are being invented both by commercial companies and by academics, and it can be a real challenge to keep up with it all and distinguish between a new capability and a dubious idea.

www.it-ebooks.info

The RepRap Movement

When some of the key patents expired on the FDM printing method, it occurred to Adrian Bowyer, a senior lecturer in mechanical engineering at the University of Bath in the United Kingdom, that it might be possible to build a filament-extruding 3D printer that could create the parts for more 3D printers (besides readily available electronic and hardware-store components.)

Furthermore, Bowyer published the designs for the parts for his 3D printer on the Internet and encouraged others to improve them and in turn post the improved versions. He called this open source concept the RepRap project and obtained some initial funding from the UK's Engineering and Physical Sciences Research Council.

Bowyer's team called their first printer Darwin (released in March 2007) and the next Mendel, released in 2009 (for more details, see http://en.wikipedia.org/wiki/RepRap_Project). The printers were named after famous evolutionary biologists because they wanted people to replicate and evolve the printers. Files to make the plastic parts were posted online, freely available, with alterations and improvements encouraged. Necessary metal parts were ideally available at a hardware store or able to be made in a garage. In practice, nozzles were available for online purchase pretty early on for people without access to machine tools to make one, and stepper motors were commodity items.

The early printers were difficult to put together and to get to print well. In the Czech Republic in 2010, Josef Prusa released a design now called the Prusa Mendel. It simplified the original Mendel design, and after that there was an acceleration in printer designs as people tried out the open source designs, modified them, and posted their own. A "family tree" of this period can be found at http://reprap.org/wiki/RepRap_Family_Tree.

Then there was a transition from making files for printer parts downloadable to making whole printer kits available for purchase. One of the better-known kits was the MakerBot Cupcake CNC, which started shipping in April 2009. It was superseded by the MakerBot Thing-O-Matic in 2010. These were mostly made of lasercut wooden parts with some 3D-printed parts (plus, of course, motors and electronics). Eventually, MakerBot became one of the earlier commercial consumer printer companies and was purchased by Stratasys in 2013.

What really caused a blossoming of different designs, though, was *crowdfunding*—websites that allow entrepreneurs to put out early stage products and take contributions from the public to fund development and early production. Because key patents for the core technologies underlying filament-based 3D printing had run out, entrepreneurs typically did not have any type of proprietary technology, which made traditional startup funding difficult to obtain. In the next section, you will see how the availability of crowdfunding enabled 3D-printer entrepreneurs to launch their startups.

The Rise of Crowdfunding

By 2009, 3D-printer development largely split into two camps: those supplying large, industrial printers (typically with some proprietary technology) and a big informal network of people working on open source RepRap or similar filament-based consumer printers.

On April 28, 2009 the Kickstarter crowdfunding platform launched (www.kickstarter.com). Kickstarter is one of many crowdfunding platforms that allow an entrepreneur to post a project and ask people to support the endeavor. Various crowdfunding platforms have different rules about the type of projects that are acceptable, and open source 3D printers are a very good fit for crowdfunding because most crowdfunding sites require a clearly defined project. Developing a 3D printer is a project with a natural endpoint, and often a printer is the reward the donor gets for supporting the development.

■ **Tip** To see the vast variety of technologies on the crowdfunding platforms, go to their sites and search on "3d printer" for printer projects and "3d printing" for ancillary technologies and design projects on Kickstarter (www.kickstarter.com) and Indiegogo (www.indiegogo.com). This material literally changes every day, and watching projects posted on these platforms is a good way to see what is being invented on the entrepreneurial side of the 3D-printing ecosystem.

---

www.it-ebooks.info

In 2012, the Form 1 stereolithography printer raised nearly $3 million on Kickstarter; in 2013, the Buccaneer filament-based printer raised about half that. Many other 3D printers have raised funding in the six figures on Kickstarter and other platforms. An ecosystem of related projects—such as printing different types of objects (jewelry, dolls, and so on) and post-processing technologies—has appeared on Kickstarter.

■ **Caution** Crowdfunding platforms do little or no review of project feasibility. You need to evaluate for yourself how likely it is that a device on a crowdfunding site will actually ever work and remember that you are backing an entrepreneur, not ordering something from a department store. Crowdfunded products may appear years late, or not in the form envisioned.

Enabling Technologies

The confluence of expiring patents on core 3D-printing technologies and the emergence of crowdfunding platforms created a ripe business environment for small inventors to get 3D printers and related products to a wide audience with very little capital. Any sudden wave of innovation like the current one in 3D printing has many components, but the development of two technologies—the Arduino and open source code repositories—had an outsized impact on the 3D-printing ecosystem.

The Arduino

In 2005 the Arduino open source microcontroller and its integrated development environment (IDE) were introduced, based on a project at the Interaction Design Institute in Ivrea, Italy. Arduinos were designed to be easy-to-program hardware/software environments for student projects, hobbyists, and the like. As it turned out, an Arduino board was also just about the right computing power to run a consumer 3D printer. Low-cost, open source, and adaptable Arduinos and their associated hardware ecosystem enabled easy system development of what might have otherwise been prohibitively complex machine control systems.

Open Source Code Repositories

Github (https://github.com) launched in 2008. It is a platform that allows software developers to work together; accounts for people working on open source projects are free. An easy-to-use system of software repositories made it easy and seamless for developers to build on each other's designs. Open source software projects existed decades before this, of course, but the Github environment made it simpler and cleaner for people to work together than before.

Many *wikis*—websites for sharing information among community members—exist as well (including the RepRap wiki at http://reprap.org). Wiki technology is much older (the first one launched in 1995, according to Wikipedia's entry on wikis) but has been a crucial part of the infrastructure development for consumer 3D printing. Chapter 2 is a discussion of open source 3D printer software.

A Case Study of Printer Evolution

If you look at the "family tree" of RepRap printers, it can be pretty overwhelming. We will follow one branch which leads from an early classic RepRap design to a successful Kickstarter-funded printer as a case study of open source printer evolution.

www.it-ebooks.info

Figure 1-3 shows the two printers: the modern Bukito (www.deezmaker.com) and the RepRap Wallace (http://reprap.org/wiki/Wallace). The man holding the two printers is Rich Cameron, who designed the Wallace in 2011 and was a crucial member of Deezmaker's Bukito team in 2013–2014. He goes by the "nom du internet" *Whosawhatsis*, and so you may find his designs by searching on that name. (He is also the technical reviewer of this book.)

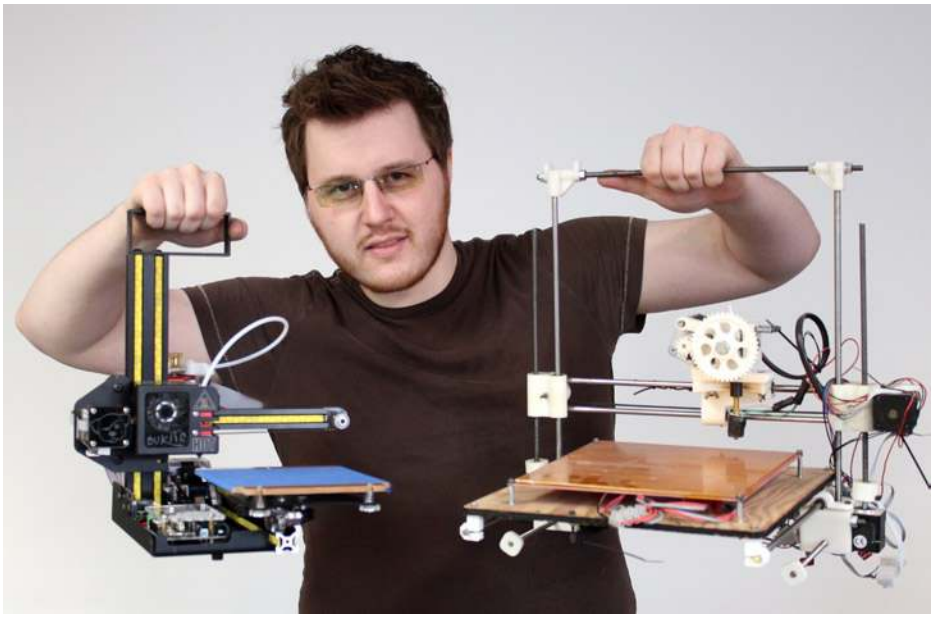


Figure 1-3. *Rich Cameron, aka Whosawhatsis, holds a Deezmaker Bukito (left) and its ancestor, a RepRap Wallace (right). Photo by Diego Porqueras*

It is quite stunning to look at Figure 1-3 and see how rapidly open source printer design has matured in a little over two years. The Wallace (named after evolutionary biologist Alfred Russel Wallace) was loosely based on the earlier Printrbot. Cameron adapted the design using OpenSCAD (which you will learn about in Chapter 5) to be simple yet robust and able to be configured in various sizes.

Cameron did not sell the Wallace; he posted the part designs on http://reprap.org/wiki/Wallace. Builders were on their own to source the parts. For a while, a German company sold a version of the design with resin-cast versions of the parts that otherwise would have been 3D printed.

The Bukito was a Kickstarter project managed by Diego Porqueras that raised $136,984 from 307 backers in a campaign that ended August 4, 2013. The Bukito will be sold in kit form by Deezmaker, a small company in Pasadena, California, where Cameron is now VP of Research and Development. Because 3D printing parts is still slow, to be able to meet demand the Bukito has few 3D-printed parts (versus the large number visible on the Wallace) and more traditionally manufactured parts.

There are now dozens of 3D-printer companies, ranging in size from public companies like Stratasys, Voxeljet, ExOne, and 3D Systems (which acquired another large player, Z Corp, in 2012) to tiny organizations with a handful of people. Some printer companies started out open source but evolved proprietary systems for either their hardware or software; others have worked to stay open source. Some have tried to keep the printed-part count up; others have bowed to the inevitable as their production runs got larger and moved to more conventional parts.

www.it-ebooks.info

There would not be a 3D-printing industry without customers. Professional designers and artists have been early adopters. However, there also has been a rise of hobbyist users associated with a social phenomenon known as the *maker* movement, which can loosely be defined as a social trend toward making things yourself, preferably things that are rather hard to make. This maker ecosystem is discussed in detail in Chapter 3.

Summary

In this chapter, we briefly reviewed how the 3D-printing industry has gotten to its current state. We focused in particular on the open source RepRap heritage printer and how it is rapidly evolving and maturing. In Chapter 2, you will learn more about the typical hardware of a RepRap heritage printer, and in Chapter 3 you will study state-of-the-art open source software.

www.it-ebooks.info

CHAPTER 2

The Desktop 3D Printer

In Chapter 1 we saw that 3D printing has a 30-year history spanning a variety of technologies. The most notable development of late has been the dramatic drop in cost and availability of 3D printers. This has been driven by the technical, legal, and societal shifts in the 3D-printing market since the major patents in the space started to expire over the last decade. Printer manufacturers now range in scale from public companies to crowd-funded (or bootstrapped) entrepreneurs.

This chapter introduces the consumer-level desktop (or perhaps, more accurately, *benchtop*) 3D printer, the major types of printers, and a bit about how they work. Then in Chapter 3 we will learn more about the open source movement, the maker phenomenon, and the business and social environments driving the rapid expansion of this market.

Who Uses Consumer 3D Printers?

Why would any normal consumer want a 3D printer? Many early adopters have been hobbyists who just want to try out the technology for its own sake. They have driven printer design forward by contributing to open source forums. The stereotypical use of a printer in the hobbyist sphere has been to print out toys, tool holders and organizers, science-fiction character figurines (Yoda heads are particularly popular), role-playing game objects, abstract mathematical sculptures, and add-on or upgrade parts for 3D printers themselves.

However, early adopters with critical applications are also starting to emerge. Product designers, Hollywood special-effects artists, and others who frequently need one-off models can use a 3D printer to make a physical model that is much easier to alter and iterate with clients than a traditional foam-core or clay one.

Chapter 9 discusses the process of integrating traditional manufacturing technologies like sand casting with 3D printing to create prototypes in metal more efficiently than is possible with traditional sculptural techniques. Small-run production also can benefit from using a few 3D-printed parts; many startup 3D printer companies use at least some 3D-printed parts for a while until their production runs reach a point where other processes make more sense. The large white parts in Figure 2-1, for example, are 3D printed.

www.it-ebooks.info

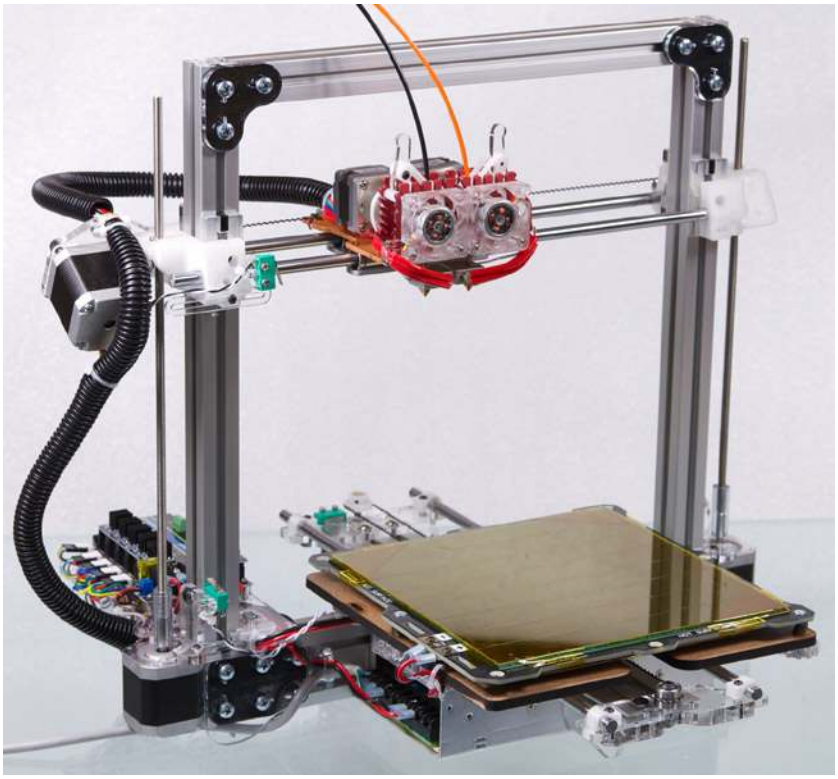


Figure 2-1. *A typical Cartesian 3D printer (a Deezmaker Bukobot Duo). Photo courtesy of Deezmaker*

At the other end of the product lifecycle, 3D printing has also found a niche in making parts to keep discontinued or obsolete equipment going a while longer. Odd-shaped fittings and brackets that are no longer made can be recreated in a computer-aided design (CAD) program and then printed. Unfortunately there's no easy way to "make a copy," particularly if the part has a lot of complex holes and internal structures that a scanner cannot illuminate well. A lot of endeavors in this area are underway, however, and by the time you read this, better solutions may be available. Chapter 4 covers the process of creating a model by developing one, scanning it in, or finding a version that has already been created online.

Personalization has also been a popular use of 3D printers. Cellphone cases are the stereotypical use here, and the online databases of objects (as described in Chapter 4's section "Downloading and Modifying Existing Models") contain a vast array of options. Once people get proficient with design software, they also start to use their printers to solve small household problems that otherwise would use duct tape and random leftovers from other projects. Little brackets to hold things in place and replacements for broken knobs, for example, are good uses.

The author's husband's first project was to create a stand to hold a container of his favorite (but rather viscous when cold) ice cream topping upside-down in the fridge so that it would always pour easily right away. Although his was a bit of a first-world problem, you can imagine that assigning a similar problem to students would be a good design exercise that could use several different disciplines.

Educators and scientists have always created models to illustrate mathematical and scientific abstract concepts; organic chemists have long wandered around campuses with construction-toy molecule models. 3D printing (and the ability to easily share and build upon models, as discussed in Chapter 4) makes the technology a natural for educational and scientific uses. In Chapter 12 we will see how educators use 3D printers, and Chapter 13 talks about some scientific visualization uses.

www.it-ebooks.info

Types of Filament-Based Consumer Printers

As mentioned, because of their convenience and ubiquity, this book focuses on printers that melt filament (spools or cartridges of material, typically either 1.75 mm or 3 mm in diameter) and lay the melted material up layer by layer to form objects. But there are now consumer-level resin printers, including those from Formlabs and B9Creations. Using one of these is significantly different from using a filament-based printer. If you have purchased an open source resin printer (such as the B9Creator), you will be able to extrapolate your processes, to a degree, from those described in this book.

The RepRap movement discussed in Chapter 1 resulted in a blossoming of different models of small, relatively low-cost 3D printers that melt and extrude plastic filament. Most filament-based desktop 3D printers on the market currently are *Cartesian*. These machines have a frame that is more or less rectangular (or at least made up of pieces at right angles). Various parts of the printer move along each of the axes to create a 3D print. (Both printers shown in Figure 1-3 are Cartesian.) Although Cartesian printers move along right-angled *x*, *y*, and *z* axes, they frequently have diagonal supports (for example, the RepRap Mendel and its descendants).

Although Cartesian printers are the most common, there are others that are not designed to move in three right-angled axes. There are several types of non-Cartesian 3D printers. One interesting non-Cartesian branch of the 3D printer family tree is the *Deltabots*. Their heritage is from pick-and-place industrial robots used in industrial applications to precisely place a part on an assembly or in a package. The following sections compare the Cartesian and Deltabot design philosophies.

■ **Note** Deltabots are the single most common subcategory of non-Cartesian, inverse-kinematics driven printers, which also includes SCARA (Selective Compliance Assembly Robot Arm) bots, polar bots, and some more obscure concepts (most of which are developed by Nicholas Seward—`http://conceptforge.org`). Seward's designs are well known in the RepRap community for using complicated *inverse kinematics* more complex than the standard delta/SCARA designs (Deltabots are explained in an upcoming section). Inverse kinematics algorithms start with a position for the print head in space and work backwards to figure out where the non-Cartesian arms should go to get the print head there.

Cartesian Printers

Figure 2-1 shows a Deezmaker Bukobot Duo, a typical Cartesian, RepRap-heritage 3D printer. 3D printers define *x*,*y*,*z* axes. Typically, the *z* axis is the vertical one. In the case of the machine in Figure 2-1, the *x* axis direction is from left to right, and the *y* axis is toward and away from you.

Figure 2-1's design has a build platform (the square platform, where the 3D-printed object will build up) that moves in the *y* axis (forward and backward in the view in the figure). The build platform rests on the *Y carriage* which moves the platform along the *y* axis.

The mechanism partway up between the build platform and the top of the frame is the *X carriage*. The X carriage carries the *extruder*. The extruder in turn has several major components. The *extruder drive mechanism* drives the filament into the *hot end* where it is melted and extruded through the *nozzle*. In Figure 2-1's design, the extruder moves left to right to create the motion in the *x* direction. The whole X carriage is moved up and down by the motors and screw gears visible on either side to give motion in the *z* (vertical) direction. Or, to put it another way, the Z carriage is the entire *x* axis.

In later sections of this chapter we will talk about each of these components. For now, the thing to notice is that everything is at right angles. Each motor drives one axis (there are two motors on the *z* axis to help lift the *x* axis while keeping it level—if there were only one motor on one side of the frame, it would be difficult to keep the *x* axis level).

www.it-ebooks.info

This design (called a *gantry*, an overhead axis supported on both ends) has the virtue of conceptual simplicity: if you want to move on the *y* axis, just one motor has to engage. (The *y* motor is at the back of the machine here and not visible under the build platform; the *x* motor is the motor at an angle on the left side of Figure 2-1). Different manufacturers make various choices about which axes to move and which parts to keep stationary. Many use the arrangement just described, but some others move either the extruder or the platform in both *x* and *y* directions. A Cartesian printer does not have to have a rectangular frame. An open, cantilevered, gantry-style frame (as shown in Figure 2-2) accomplishes the same thing. Because the frame needs to be very stiff to keep the precision of the print high, a gantry is best for smaller build area printers where the extruder is not suspended too far out on a beam.

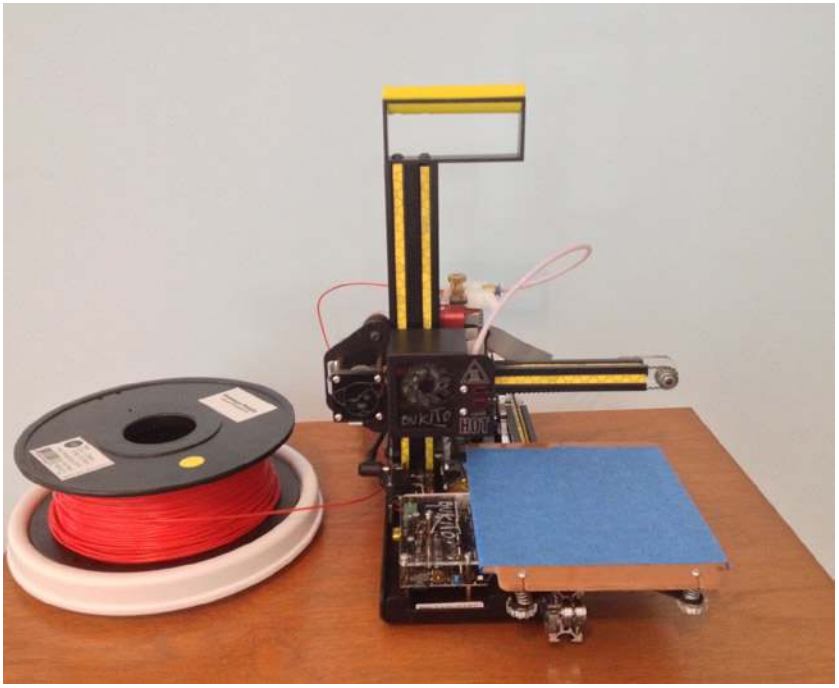


Figure 2-2. *A cantilevered, gantry-style Cartesian 3D printer (Deezmaker Bukito)*

Figure 2-2 shows a Deezmaker Bukito 3D printer, which has a 5×6-inch platform and a maximum height of 5 inches. (By contrast, the printer in Figure 2-1 was designed to print objects up to those that fit into an 8-inch cube.) This machine moves the extruder from right to left (*x* axis), moves the platform forward and back (*y*), and carries the whole *x* axis up and down to get the *z* (vertical) dimension.

Deltabots

The Deltabot design (Figure 2-3) is an alternative to the Cartesian. The extruder is attached to an end effector at the intersection of three carriages. The carriages move in tandem for *z*-only motion, but *x*-*y* motion (the plane parallel to the build platform) is controlled by their relative positions, so they spend more time moving in opposition to one another than in tandem. The carriage geometry is set up such that the extruder will move in *x* and *y* keeping the nozzle pointed straight down at all times. This type of Deltabot is called a *linear delta robot*. For applications other than 3D printing, rotational actuators are more common than linear actuators.

www.it-ebooks.info

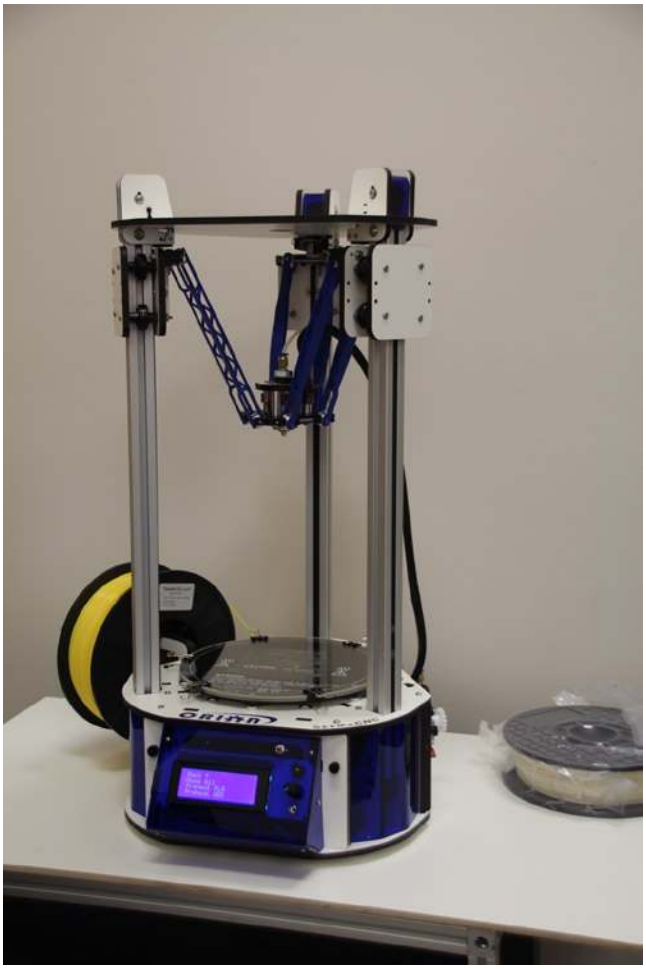


Figure 2-3. *A Deltabot 3D printer (the SeeMeCNC Orion). Photo courtesy of SeeMeCNC*

Deltabots carry very little weight on the end effector and can therefore move very fast, and a lot of the mechanisms are mature from their pick-and-place robot heritage. There are also not a lot of constraints on how big the machine can be. Determining the theoretical resolution of a print in the *x-y* plane is more complex for a Deltabot than for a Cartesian.

As with all things in 3D printing, there is a lot of work ongoing in this sphere, and you should expect both Cartesian and Deltabot geometries to continue to improve. The layer-height-versus-accuracy discussions in the remainder of this book are focused for the most part on Cartesian geometries.

■ **Note** A Deltabot's motion is hard to describe and fun to watch, so if you are having trouble imagining how this works, search online for "deltabot 3D printer" videos.

---

www.it-ebooks.info

Kits vs. Assembled Printers

Many 3D printers are sold as kits, and you assemble the printer. This has the virtue that you end up understanding the printer and how it works as a system much better than you would had you just bought the system off the shelf. Putting together a kit enables you to be better prepared to make adjustments in hardware and software later on, because the reality is that, to be able to print well, most printers require significant knowledge of how the system works.

The counterargument of course is that someone (or some robots) who assemble electronics all the time are more likely to do a good job than you are. This area is in flux too; as software gets more sophisticated and printer designs continue to improve, knowing the details may become less important. But for now, it really helps to know how the machine was built and what the likely culprits are when there are problems.

■ **Tip** If you are deciding whether to buy an assembled printer or a kit, note that most manufacturers post assembly instructions online. You can always look at the instructions before you buy and decide whether the assembly is within your skill and time limitations.

3D Printer Design Considerations

In the rest of the book we will talk about parts of the printer, and we will introduce them now with some pictures so that you know what we are talking about later on. A filament-based 3D printer has been called a computerized hot glue gun: basically it takes plastic filament, melts it, and puts it down in layers. There are several key components in this requiring many design tradeoffs among the various options.

Filament

Chapter 7 discusses filament and its handling in great detail. Filament typically comes on spools (for open source printers) or, in some cases, in proprietary cartridges. Printers need to have some means of getting filament off the spool by allowing the filament to turn on a spindle or a lazy-susan-type tray. In some cases, this is part of the frame or attached to it; in other cases, the filament rests on a lazy susan next to the printer.

Frame

As noted earlier in the chapter, the frame of a printer needs to be stiff and sturdy for the prints to build up accurately. If the frame is sloshing around, it is unlikely that you will be able to have an accurate print. Various types of aluminum, extruded rails typically make up frames. Laser-cut or 3D-printed joints typically make up the rest of the frame.

Build Platform

Every 3D printer needs to have a flat surface to build the print. This surface is commonly called *the build platform*, or sometimes just the *platform* or *bed*. Some printers have a heated platform to allow printing of materials that need to be kept warm during building. Others just have a glass or other plate that needs to be covered with tape of some sort to ensure that the first layer of the print will stick.

The printer in Figure 2-1 has a heated platform covered with Kapton high-temperature tape. The one in Figure 2-2 is unheated and covered with blue painter's tape to allow printing of a plastic called PLA (polylactic acid). Chapter 7 details what type of build platform surface is necessary for different filament types.

www.it-ebooks.info

Extruder Design

The extruder is the part of the printer that melts and moves the filament. The extruder has several parts. One is an extruder drive mechanism, which is a motor and a mechanism that pushes the filament into the hot end. The hot end in turn is comprised of a heater, a nozzle, and a sensor (a thermistor) to sense how hot the bed is. You can see two extruders on the printer in Figure 2-1, which is a dual-extruder machine capable of printing objects out of two materials.

Bowden and Direct-Drive Extruders

There are many different extruder designs, which fall into two major categories. A *direct-drive extruder* (like the one on the machine in Figure 2-1) has a motor and drive gear pushing the filament right next to the hot end. A Bowden extruder (like the one on the machine in Figure 2-2) has a drive gear that is separated from the hot end with a guide tube.

The main reason for using a Bowden extruder is that it moves the heavy motor away from the nozzle, which can make the part of the extruder that is moving a lot lighter. This can allow for faster printing speeds, but at the cost of a more complex extrusion system.

Retraction

When the printer is creating a layer, there are holes and filled areas. Some of the holes can be made by having the nozzle zip around the edge of the hole. Sometimes, though, it is necessary to stop extruding across a gap in the layer. In that case the extruder has to *retract* the filament. The drive gears need to be able to pull filament back as well as push it forward to make this work. How much to retract during a print is something a user can set during the process of slicing a model into layers (discussed in Chapter 5). Retraction has a strong effect on print quality.

Nozzles

The nozzle is one of the most critical pieces of the printer and one of the more delicate ones. The holes are tiny and easily clogged. To a degree, the nozzle material and quality define what materials your printer can safely melt and therefore print. Good-quality nozzles can handle polycarbonate, nylon, and other higher-temperature plastics. The nozzle is part of the hot end, which includes the nozzle, the heater block, the thermal break (barrel), and, in many designs, a heat sink to cool the top part of the thermal break. Some designs depend on the insulating properties of high-temperature plastics or, occasionally, ceramics (at the cost of being able to extrude higher-temperature materials).

Moving Parts

3D printers need to move some combination of the extruder and the build platform to be able to create objects. They achieve this with a combination of stepper motors attached to drive screws or cable, belt, or other systems attached to pulleys.

A stepper motor (Figure 2-4) is a precise, brushless, direct current (DC) motor that moves the shaft in predefined angular steps. Motors for 3D printers typically have 200 steps per revolution. The stepper motor is then coupled to a drive screw (like the *z*-axis motors for the printer in Figure 2-1) or to a belt or cable.

www.it-ebooks.info

Figure 2-4. *A stepper motor*

Filament needs to be carried somehow, too. Open source printers typically take filament from a spool, which needs to be mounted to turn freely somehow (the extruder drive gear drags the filament; the spool is not motorized). Figure 2-2 shows a typical rotating spool lazy susan.

■ **Tip** You may see values cited for the accuracy or resolution of your 3D printer. This topic is discussed in Chapter 5's section "Effects of Layer Height." It is worth mentioning here that that minimum step size (often quoted) is not necessarily the same as the minimum possible layer thickness. Other inaccuracies of the system and the width of the nozzle will dominate the accuracy uncertainties once you start to get that low.

---

www.it-ebooks.info

Control Electronics

Chapter 1's section "Enabling Technologies" discussed the Arduino open source standard. Many open source printers are controlled by Arduino-compatible microprocessors. The control systems are pretty simple. Most consumer-level 3D printers are mostly *open loop* systems. This means that the microprocessor sends a command but does not have any way of knowing whether the command executed correctly or not.

There are a few exceptions to the general open loop strategy. Any heated element in a printer (an extruder or heated bed) has a thermistor temperature sensor. Otherwise, it would be impossible to know how to manage temperature. Similarly most printers have *end stops*. These allow the machines to home to a known position, after which they count steps in each direction to know how far they have moved from that point.

Machine Tool or Computer Peripheral?

A 3D printer somewhat lives in its own category. The name is unfortunate; it probably has less in common with 2D paper printing than it does with other machine-shop processes like milling. Using a 3D printer well requires both computing ability and a little bit of machine-shop knowledge. One person does not often know both areas, so if you come at this from one side or the other, consider pairing up with a partner from the other extreme to learn the technology together.

Where should you put your 3D printer? It is not superficially as dirty as traditional shop-class machine tools are, and in fact it's not a good idea to have a 3D printer in a dusty shop. If you know you have a lot of fine particles in the air, be sure to use the dust-management suggestions in Chapter 11's section "Dust."

But do you want it in an office environment? If you are post-processing, you might want to do that in a professional studio or your garage (see Chapter 9 and 10). If you are printing with materials that have a strong odor, like ABS, you probably do not want that in your office environment either.

3D prints also take a long time; print jobs that take days are not uncommon. So, you want to have a place where people will not trip over the printer or interrupt it partway through.

Finally, you will find yourself buying tools and useful widgets from a range of retailers. Appropriate metric screwdrivers and hex drivers can be found online (see what your particular machine requires first). Tools for taking prints off the build platform and for post-processing can often be found in artists' supply stores. Chapter 11 discusses these in more detail.

Safety and Ventilation

3D printers need to be treated with respect because of the machine-tool aspects of their personalities. In general, use common sense and follow manufacturer's instructions. Here are a few things to also consider:

- The hot end is as hot as the inside of an oven baking a cake, and heated platforms can be pretty hot too. Take the same precautions as you would when dealing with any other hot surfaces and do not grab the nozzle or swipe excess filament off with your finger.
- The printer is a moving robot. Do not stick fingers into it when it is operating.
- If you are going to assemble a printer yourself and you are a bit rusty on electronics assembly, find someone with more experience to mentor you and review the results—or take a class. Look for a Makerspace near you to learn more skills.

www.it-ebooks.info

- Keep the area around your printer well ventilated, but remember to draw air away from it; do not have a draft blowing on the printer directly.
- Do not leave your printer unattended, and be sure you are able to hear it while it is running. Bad mechanical noises are typically the first sign that something has gone wrong.

Summary

This chapter covered the design and major components of a consumer 3D printer. We also saw that there are two common geometries for filament-based printers (Cartesians and Deltabots) and learned about the design tradeoffs between the two. Finally, we talked a bit about how to think about a good environment for the printer. In the next chapter, we will learn about the open source movement, how that has affected this type of printer, and the effects of the maker movement on the 3D-printer markets.

www.it-ebooks.info

CHAPTER 3

Open Source

This book focuses on open source 3D printers. *Open source* is a philosophy, and does not refer to any particular type of design. Being part of an open source development community means that you use software or hardware that others have developed and posted online for public use, and that you in turn agree to share what you develop based on those earlier designs. In this way, very complex systems can be developed very rapidly.

But why would anyone post their hardware designs or software as open source? First, it is a very efficient way for technology communities to experiment and find good ways through a lot of possible growth paths. Often, open source means pure altruism mixed with a desire for community recognition. One downside of open source software is that people work on areas that they most care about, and that can mean that some features are developed earlier or later than might be best for all. It also means that the software or hardware (as the case may be) will change a lot, and unpredictably, if no one is doing centralized releases.

The open source software discussed in this book by and large has a volunteer curator (or one supported by donations) and as such offers reasonably orderly build cycles and updates. The open source attitude is compatible with the user community of *makers* (people who like to build, tinker with, and change things themselves, described later in the chapter). Makers have helped evolve an ethos that celebrates open source 3D printing's very open sharing and rapid adoption of improvements.

Open source started as primarily a software phenomenon. One of the first communities evolved at MIT in Cambridge, Massachusetts. As open networks like Usenet and later the World Wide Web proliferated, it became possible for geographically dispersed developers to share code. The RepRap community has extended this concept to both hardware and software for 3D printers (like the Wallace in Figure 3-1). This chapter introduces the open source and maker communities and discusses 3D printing (particularly RepRap printing) and its place in those communities.

www.it-ebooks.info

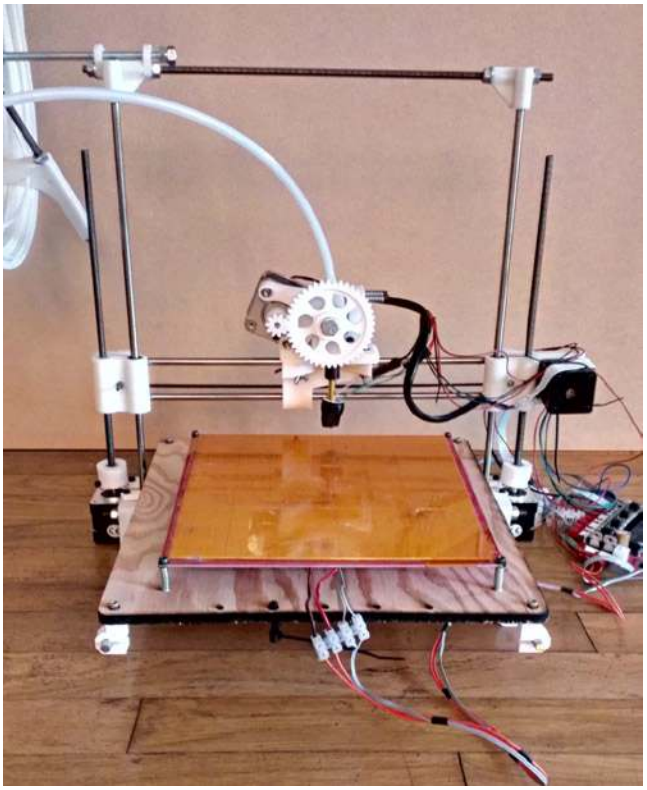


Figure 3-1. *The Wallace open source printer. Photo courtesy of Rich Cameron*

Open Source Infrastructure

A significant infrastructure supports the open source movement, including shared licenses, repositories, wikis, and forums. This section talks about the licensing standards and online community communications tools and repositories that make it possible to share information and jointly develop code. The rest of the chapter looks at other recent drivers of open source 3D printing markets, with a particular focus on the maker movement.

GNU Licenses

Open source ecosystems are not lawless places; on the contrary, open source community participants are usually acutely aware that they need to protect their work so that someone else cannot come along and patent it or otherwise make it proprietary.

Very often open source software or hardware is released under a GNU License. (*GNU* is a recursive acronym that stands for *GNU is Not Unix*, according to the Free Software Foundation.) There are various nuances and variations of GNU licenses, but fundamentally a GNU license says that you release your work so that others can use it, and anyone who builds on your work is obligated to put their work out freely too. A GNU Public License (GPL) only requires you to share source code if you distribute your software to others, who in turn will have similar restrictions. Said another way, it prohibits distribution of products made with the open source code (for instance, by selling them) without making the source code available under the same terms.

www.it-ebooks.info

Putting out the source code freely does not mean, however, that you cannot charge for work put out under a GNU license—you can, but you have to put the code or hardware design out freely. Many RepRap 3D printers operate under variations of this philosophy. It does mean, however, that if someone else decides to produce something you put out there, they can. For a business, this means that you need to execute well and innovate continuously, because otherwise anyone can (and might) start where you left off and invent past you. Of course, then you can in turn try to pass them. It should be clear how this model leads to a high rate of both incremental and radical innovation, but it does depart from the way many business models work now. How this licensing scheme will play out in the 3D printer market remains to be seen; Chapter 14 speculates on this a little.

■ **Tip** GNU License information and sample licenses are available from the Free Software Foundation at `www.gnu.org/licenses/license-recommendations.html`. One common GNU license is the GPL (GNU Public License). The Creative Commons license is a similar set of licenses for creative works (writing, art, and so on). It is available from `http://creativecommons.org/licenses/`. Designs for 3D-printed objects are often shared under Creative Commons licenses. There are several types of Creative Commons licenses, including a "noncommercial" license that allows others to use your work as long as they do not charge for it. You should, of course, consult a legal professional if you are embarking on an open source endeavor (particularly a commercial one).

Wikis, Forums, and Open Source Repositories

Wikis are community repositories of knowledge about a particular subject that can be edited easily by members of the community. The best known is Wikipedia (`www.wikipedia.org`). Some wikis are *closed*—meaning only people approved by a moderator can post information. Others (like Wikipedia) are open, and essentially anyone who does not run afoul of the site's rules can post. Wikis are generally thought to have originated in 1994, when Ward Cunningham developed the first one around software design topics.

Many open source projects depend on a wiki for documentation and shared information about the software and how it works. Because the software will change a lot, an easily changeable wiki is a good way for developers to update small parts of the community documentation without a major release. The RepRap wiki (`http://reprap.org`) is a core resource in this area. Check to see whether your printer's manufacturer maintains a community wiki or forum.

Forums are online discussion groups that are often but not always associated with a wiki. In forums people can discuss topics actively, whereas wikis are more oriented to storing information that the community generally agrees upon (or at least storing the collective information, including branches for areas where people disagree). The RepRap community forum (`http://forums.reprap.org`) is one place to look for 3D printing discussions; your manufacturer likely supports a forum as well.

Finally, open source repositories are designed to allow different people to modify computer software in an organized way so that changes by one person do not break code developed by another. The rest of this section discusses these three types of information sharing and their strengths and weaknesses. All three are used heavily in the open source 3D printer community.

Wiki Accuracy

How accurate is a wiki, or open source information online in general? Since you may be depending on wikis and forums for some of your tech support, it is good to have some benchmarks about how accurate community-generated material can be. One case in which a well-known wiki was evaluated reasonably objectively is described here.

www.it-ebooks.info

In wikis (particularly open wikis), anyone can edit, add, or delete material; contributions of experts and the general public carry the same weight. For this reason, the academic world typically has not treated Wikipedia (or any wiki) as a credible source. However, in 2006 the British scientific journal *Nature* (one of the most selective peer-reviewed journals in the world) commissioned a blind study in which scientists were given selections from Wikipedia and from Encyclopedia Britannica Online. They were asked to tally errors they found in the selections. To everyone's surprise (and Britannica's public objections), the error rates were essentially the same. (For *Nature*'s page on the subsequent controversy, see www.nature.com/nature/britannica/index.html).

An encyclopedia is a general-interest publication, of course, and one could argue about whether this is a good metric for specialized information about 3D printing. For detailed technical information, it is a good idea to evaluate anything surprising or counterintuitive on a wiki with care. Another issue with wiki documentation is that topics that are "obvious" to an expert may be missing entirely, which can be challenging to someone new to a field. This has often been the case with 3D printer wikis. Often there is a lot of detail on specific aspects of interest to an expert, but a broad overview might be brief or missing, and it can be challenging to wade around wikis, forums, and whatever your search engine finds to locate what you need. Because of the lack of a central editor, there can be gaps in coverage of some topics, or duplications and inconsistencies. Do not expect a wiki to have exhaustive, non-duplicative coverage of topics. Of course, if you find holes or inconsistencies in wiki documentation, you can always fill them yourself to continue to develop the community, too.

The RepRap Wiki

The open source printer community has maintained a central wiki at www.reprap.org covering the design and operation of open source printers with heritage in the RepRap project (described in Chapter 1). Individual projects or printers may also have their own wikis. In some cases the wiki, or just some parts of it, may be moderated to manage changes and to be sure that a core set of information is not deleted.

Forums

As mentioned earlier, often wikis will have an associated forum, an online discussion group where users can pose or answer questions. Some forums are managed or self-moderated better than others, and so some may have threads that are relatively well-organized, whereas others may be a bit more of a tangle. In general, until you know where good forums are, you can just try doing a Google search on the name of your printer and add a few key words describing the issues. Some official websites will come up, but forums will as well.

As with a wiki, unless you are getting an official answer from a forum moderator or company representative, you should take any suggestion in a post with a grain of salt. If you find contradictory information, don't necessarily assume that if two people say one thing and one says another that the two people are right. One might have found the other's post and quoted it. The number of people saying something, unfortunately, is not necessarily a good indicator of accuracy in community forums.

Open Source Repositories

Open source development needs places to store and share computer code. One of the bigger repository hosts is Github (https://github.com), which in 2014 claimed to host 13.8 million repositories, with 5 million of those being open source projects.

Github has both free repositories and private, fee-based ones for people working on commercial projects. Repositories allow users to modify code in different, parallel ways without stepping on each other. Of course, this can lead to an explosion of versions, and maintainers of repositories need to come up with rules to keep things from getting out of hand.

www.it-ebooks.info

■ **Tip** If you want to see how to start or explore existing Github open source projects, you can start with https://guides.github.com/activities/contributing-to-open source/ for some background and details of how it works.

Open Source Pros and Cons

The pros and cons of open source software really both boil down to one fact: it is easy to change code, documentation, or hardware plans, as the case may be. This means that if there is an error or bug it can be remedied quickly by the community. On the other hand, if you are counting on using an open source platform, you have to think hard about how to manage configuration control and updating of your system in tandem with the state of the open source software. Over time, big programs that are used by a lot of people may, in one way or another, support one or two people to manage the overall program to do controlled version releases.

Open source documentation has similar version control and completeness issues. Some programs have wonderful documentation that rivals or exceeds the standards of commercial documentation. Some others may offer a lot of detail on individual features that is appropriate for an advanced user, but lack "big picture" documentation that would be useful for a first-time user trying to figure out how to get started. The documentation may lag behind the software and reflect an older version.

While writing this book, we have had to allow for the fact that open source software can and does change on a daily basis. That is why we have a very limited number of screen shots and have tried to focus more on how the software (and the community that maintains it) *thinks* and (broadly) what it is *doing*, rather than describe necessarily exactly how it *looks* or give a detailed, item-by-item list of recipe steps for using the open source software needed for 3D printing.

Meeting the Open Source 3D-Printing Community

Open source used to be a term primarily applied to software. However, the RepRap printer project and the availability of cheap microcontrollers like the Arduino (see Chapter 1) have also created a significant open source hardware community. The availability of a wide range of hardware and software has enabled a social phenomenon called the *maker movement*. Simply put, after many years of innovation in the virtual realm (e.g., video games), there is a newfound interest in actually making physical things with your own hands. Open source software and hardware, along with consumer 3D printers, has been an enabler of this movement.

To take full advantage of being part of an open source community, trying to meet some of the people who have been practitioners for a while is a good idea, as is joining online communities and forums. The 3D-printing community has a significant overlap with the growing maker community described in this section.

Maker Faires and hackerspaces are good places to do just that. Maker events, hackerspaces, and makerspaces are proliferating in many places; a little hunting around online will likely reveal a space or event nearby where you can meet some of the local luminaries in person.

The Maker Movement

People have always made things as a hobby: baked goods, knitted items, quilts, model airplanes. But after easy-to-program, open source Arduino microcontrollers became available in 2005, interest in electronics DIY (do-it-yourself) endeavors began to climb. In 2006, the first Maker Faire was held in San Mateo, California.

Maker Faires are events with a wide variety of hands-on activities, where both hobbyists and professionals show off their creations (see Figure 3-2 to get an idea of some activities at New York Maker Faire in 2013). According to Make Media (which runs the Faires), the 2013 flagship San Mateo event drew 120,000 attendees and 900 exhibiting makers. There was even a Maker Faire at the White House in June 2014.

www.it-ebooks.info

Figure 3-2. *A directional sign at the 2013 New York Maker Faire*

You will notice in Figure 3-2 that 3D printing was featured at the 2013 New York Maker Faire. 3D printing is always well represented at Maker Faires and has to some degree grown up along with it. There are always many 3D printers and applications of 3D printing on display at a Maker Faire, and many practitioners go to the Faires to meet up with each other and trade ideas and techniques in person (augmenting the online collaboration that goes on all the time).

Chapter 12 talks about using 3D printing in a classroom. Outside the classroom, though, many young makers are trying out 3D printing and electronics, often teaching themselves or begging their way into classes that were intended for undergraduates. Many school districts have discontinued shop classes because of liability concerns or perceived lack of interest, but such cuts are a disservice to students who would have learned math and science most effectively in a hands-on class. 3D printing is a way to blend student interest in the virtual world with the real-world problems of getting a physical object made.

Some students *really* get into the maker ethos. Quin Etnyre (Figure 3-3) has designed his own line of Arduino-related products under the brand name Qtechknow (`qtechknow.com`). Figure 3-3 shows a photo taken at the 2013 New York Maker Faire with some of his demonstration hardware. He was 12 years old at the time. This year, he is helping others define what should be in makerspaces for kids.

www.it-ebooks.info

Figure 3-3. *Ethan and Quin Etnyre at Qtecknow's display, New York Maker Faire, 2013. Photo courtesy of Karen Mikuni*

Makerspaces and Hackerspaces

Another option to sample 3D printing is to visit a local hackerspace or makerspace. These terms are used somewhat interchangeably to mean a place where you can go to take a class or watch people make things with 3D printers, laser cutters, and/or conventional machine tools. Some have a membership model where you can take a class to get certified to use equipment and then do your own projects.

Libraries in many cities are putting in makerspaces with 3D printers. Some government entities have funded spaces to encourage entrepreneurship and new product development. Other organizations have tried to use DIY training as a catalyst for social change. Figure 3-4 shows Luz Rivas, the founder of DIY Girls (an organization discussed in Chapter 12's section on innovative DIY programs) participating in a hackerspace's Arduino workshop.

www.it-ebooks.info

Figure 3-4. *Learning at a hackerspace*

■ **Tip** A good way to understand the maker philosophy and see cutting-edge applications of 3D printing is to go to a Mini Maker Faire near you. You will find a list of upcoming events around the world at www.makerfaire.com. You also might look to see whether there is a meetup near you of people interested in DIY projects in general or 3D printing in particular (www.meetup.com).

Many makers consider crowdfunding (discussed in Chapter 1) as a way to start their projects. Open source DIY projects are often a natural fit for crowdfunding, and many projects at Maker Faires had their start as Kickstarters or other crowdfunded projects. Hackerspaces and makerspaces can be resources for creating low-cost prototypes and meeting team members for entrepreneurial endeavors generally.

■ **Tip** If you want project ideas, the organizers of Maker Faires also publish *Make* magazine (www.makezine.com). Hackaday (www.hackaday.com) and Instructables (www.instructables.com) also have a wealth of project ideas with varying degrees of difficulty.

---

www.it-ebooks.info

Contributing to the Open Source Community

It is easy to forget that any open source community runs mostly on volunteer energy. The maker movement tools (particular 3D printing and Arduinos) are making it vastly simpler to prototype new products, including new printing and electronics technologies. This virtuous cycle means that the overall cost of hardware innovation is falling rapidly, with (imperfect) parallels to the software revolutions of the 1980s.

If you see the promise of the open source 3D printing ecosystem, or even of the wider maker movement, consider doing one of the following:

- Learn about an aspect of hardware or software and begin to contribute technically on Github, or wherever the project is hosted.
- Review documentation and contribute on wikis or forums to make things easier for future users.
- Participate in online or in-person events or join a hackerspace or makerspace. Team up with others and start inventing!

Wherever you decide to contribute, you will know that you are taking part in a large social experiment that is changing how the world innovates, one line of code and piece of hardware at a time.

Summary

In this chapter we learned how the open source community works together on a mostly volunteer basis to make rapid technological progress. The chapter reviewed the tools needed to manage the open source ecosystem, and discussed some of the pros and cons of open source software systems. Finally, we reviewed the bigger social phenomenon of the maker DIY movement and how its creation is somewhat intertwined with 3D printing and other enabling technologies.

This concludes Part I, which gave you an introduction to 3D printing and the desktop 3D printer, and ended with a discussion of the open source maker community that is moving the technology forward. Part II (comprised of Chapters 4–8) will teach you the nitty-gritty of using an open source 3D printer.

www.it-ebooks.info

PART 2

The 3D Printing Process

The five chapters in this part get into the nuts and bolts of using a 3D printer. When you create a piece on a 3D printer, you walk through a few basic steps:

- Deciding what you want to make and then scanning in, downloading, or creating a 3D computer model (Chapter 4).
- Selecting the material(s) you will use (introduced in Chapter 5 and detailed in Chapter 7).
- Slicing the model into printable layers (Chapter 5).
- Creating commands for the printer to execute and loading those commands onto the printer (Chapter 6).

The process can seem a little overwhelming at first, and many are working on making the process easier. Over time, it is likely that some of the details of the process will be automated away from the user, either in proprietary front ends for specific printers or more broadly as industry standards emerge. Chapter 8 walks through some typical end-to-end examples, so that you can see how it all fits together.

www.it-ebooks.info

CHAPTER 4

Making a 3D Model

Your first step in using a 3D printer will be to create a 3D computer model. You do that by scanning an existing object, downloading a model from the web, or creating a model yourself. In each case, there are a lot of options to choose from. There is more to design than picking a software package, though, and there are design decisions you can make that can simplify the printing process.

This chapter first covers the basic file requirements for a 3D printer. Then it reviews some options for scanning and downloading 3D models. Finally, the chapter looks at 3D computer-aided design (CAD) and CAD-related programs that you can use to make a 3D model. By the end of the chapter, you should have a computer model that's ready to go on to the next stage of processing.

What Makes A Model Printable on A 3D Printer?

Models can be made from scratch using a 3D CAD program. Such programs focus on visual effects and animation, engineering, architecture, and so on. Some 3D CAD programs are intended for simple beginner projects. If starting from zero seems daunting, you might consider downloading a pre-existing model from a database. Once you have it, you can print it as-is or modify it. Regardless of the source of the model, the file has to be in a format usable by the programs, which "slice" the model for 3D printing, as you will see in Chapter 5.

3D Model File Formats

The term *3D computer model* is used in many different contexts, which can cause confusion when someone wants to print something using a 3D printer. In this book, *3D computer model* means a computer file that contains enough information about the surface of an object to allow the object to be printed. In the open source consumer 3D printer world, the most common file format is the STL file. This acronym is sometimes said to stand for *STereoLithography* and sometimes for *Surface Tesselation Language*.

STL is something of a lowest-common-denominator file format, consisting essentially of a long list of triangles that collectively cover the surface of the object. This is not a terribly efficient format (particularly in its ASCII version, which is a text file), but it has the virtue of being relatively simple to generate and deal with and therefore has become a de facto standard. STL standards exist for both ASCII and binary file versions.

On a Windows computer, you may get an error when saving or moving around an STL file. On Windows, the STL filename extension is presumed to mean Certificate Trust List, and STL files will show up that way in directory listings. STL files will work with 3D printing programs on Windows machines, but sometimes opening the file or saving them will result in an error message complaining about Certificate Trust Lists.

www.it-ebooks.info

■ **Tip** The open source program MeshLab (available at http://meshlab.sourceforge.net) is able to translate many different types of files into STL. It can also fix the problems that sometimes occur during translation or as a result of printing incompatibilities in the original model itself.

A variety of other 3D modeling formats have evolved in specific industries and for particular modeling needs. This book focuses on the STL format. Should you find yourself with a different file format, a quick online search will usually reveal a translation program. The other common format, OBJ, is similar to STL but also preserves color (and some other) information.

■ **Note** STL files only contain information about the shape of the surface. No information about color remains in an STL file. For 3D printers with multiple extruders capable of printing in multiple colors or materials, an AMF file (which stands for Additive Manufacturing File format) is used. Chapter 8 discusses the AMF format in the context of a discussion on multiple extruders.

What Does "Watertight and Manifold" Mean?

Models for 3D printing need to be *watertight* and *manifold*. A *watertight* object, as the name implies, does not have holes in its surface. A *manifold* object means that every triangle edge is shared by two and only two triangles. Sometimes a solid object will be created in such a way that there are several "objects" sharing the same space, which will confuse matters later on. You may be able to use the MeshLab program noted in the preceding tip to correct the problem of objects in the same space, and slicing software is slowly getting better at fixing this during the slicing process. Models that are not watertight and manifold will generate errors later in the "slicing" part of the process, which you will learn about in Chapter 5.

Scanning a Model

One way to get a model of something that already exists is to 3D scan it. Scanners at the consumer level are still a bit too complex to use easily. Most of them, in one way or another, scan a large number of images of an object from many angles and create a *point cloud* representing the object. The images have to be taken in a particular way to be able to re-create the third dimension of the image.

A point cloud is what it sounds like: a large number of unconnected points that represent the shape of the object to some degree of precision. Low-cost scanners capture images from many angles to generate this point cloud using smartphone or video game cameras. Then, either the user has to manually stitch together the images or the software does it. More expensive systems use lasers to illuminate the object and create the point cloud.

Stray reflections, interference from objects in the background, and internal or concave surface features are challenging for the current crop of low-cost scanners. Resolution is a tricky thing to define accurately in these circumstances. Selection of a scanner for a given application will depend on the need for speed of capture, the accuracy required, the amount of time that can be devoted to manual cleanup, and the types of materials being scanned. Shiny and floppy things pose particular challenges.

After the stray reflections and other artifacts are removed, a scanner's software will create triangles covering the surface of the point cloud. This generates a model of the surface in the form of an STL or other format file. This process is typically referred to as creating a *mesh*, or *meshing*. For a complex model, meshing can take a very long time. Typically, the output of a scan will need some cleanup, as mentioned, to make it watertight and manifold.

www.it-ebooks.info

Consumer-Level 3D Scanners

If you're considering purchasing a scanner and your budget is limited, there are several ways to go:

- Check out crowdfunding sites like www.kickstarter.com (search for "3d scanner") to see the latest developments as well as progress of previously funded systems.
- If you're a do-it-yourselfer, check out www.instructables.com to see some DIY scanning systems.
- To try using your smartphone as a scanner, download Autodesk 123D Catch at www.123dapp.com/catch.

CT Scanners

Scientific users of 3D scanning and printing may need detailed, high-resolution information about biological structures. Medical professionals and those with access to computerized tomography (CT) scanners have been using CT scans as a starting point for 3D printing. CT scans can capture internal and complex, concave structures. CT scanners are not consumer items, but if you're a scientist or researcher, you might see whether a local hospital or research center offers scans on a fee-for-service basis. Different CT scanners can handle different densities and sizes of objects.

There are also "micro-CT" scanners with smaller beam sizes. University imaging centers and labs buy these smaller scanners for research projects, but often they're not used full-time, and the facilities will rent out time on them. Facilities with micro-CT scanners are not cheap, and thus neither are these scans. But if you are solving a real problem, micro-CT scanning may be a powerful way to get the information you need to create 3D models of structures of interest.

CT scanners usually output a DICOM file. A web search will reveal various free and proprietary tools to convert DICOM files to STL files, depending on the specific application at hand. An emerging freely available conversion package is InVesalius. Do a web search for their download page. Figure 4-1 shows a CT scan of a skull printed in metal (not on a consumer printer) by Scott Camazine.

Figure 4-1. *A 3D printed skull based on a file from a CT scan, © Scott Camazine*

www.it-ebooks.info

Downloading and Modifying Existing Models

Sometimes a model of something that you would like to print already exists. In that case, you may be able to download it from one of a growing number of model databases. Some databases contain fun items and household objects. Some of the existing models in databases are of complex, specialized objects that might be very useful to you professionally.

Models of Everyday Things

Many databases of 3D-printable objects are available online. The Thingiverse (www.thingiverse.com) and Youmagine (www.youmagine.com) websites both feature a wide range of objects, from sci-fi figurines through parts to enhance 3D printers. These models have been contributed by users and as such vary widely in the quality of their design both for printing and for their intended purposes.

Sometimes model creators will upload both the STL file for printing and the file in the original format of the software that created the model. That means if you happen to be conversant in the original program, you can start with an object and modify it. For example, in Thingiverse, when you click the Download This Thing! Button, you get both a list of the available files and the type of license under which it is being made available. Sometimes the developer just wants you to credit them if you use it. Sometimes commercial use is not allowed. If you obtain something from one of these databases, be sure to look carefully at the requirements, particularly if you're going to modify the object or sell something based on it.

The Instructables website (www.instructables.com) often includes instructions for the entire workflow to create and print a 3D model. Although not a 3D-model specific site, Instructables is a good place to start out because many models include fabrication instructions in addition to an STL file. Sometimes the instructions even extend to how to use the object. Instructables is a community website with all content contributed by its users. As of early 2014, the site stated that it had over 100,000 different sets of instructions covering everything from cooking to lab equipment.

Specialized Databases

Chemists and biologists visualize complex molecules and analyze how these molecules will interact. The Research Collaboratory for Structural Bioinformatics (RCSB) manages the Protein Databank (PDB) at www.rcsb.org/pdb/. Anyone can search this databank to find collections of published data about nearly 100,000 protein structures (as of early 2014). These structures are identified by a PDB ID, which is a four-letter or number code. Once a user finds the PDB ID, the user can use a program that can then take the ID and generate an STL file for printing. The following are two such programs:

- Chimera, from the University of California, San Francisco: (www.cgl.ucsf.edu/chimera/)
- Visual Molecular Dynamics (VMD), from the University of Illinois at Urbana-Champaign: (www.ks.uiuc.edu/Research/vmd/)

Both programs have extensive documentation. They are freely available, but have some restrictions on commercial use.

■ **Note** Do not assume that an STL file you download from a site is perfect or that it will work on your printer. It is usually wise to run files through MeshLab (see Tip earlier in this chapter) or a similar program to see if they are watertight and manifold. On download sites that allow comments or that have an "I made one!" contribution area, see whether anyone besides the author *has* made one. If not, that might be a bad sign.

---

www.it-ebooks.info

Creating a New Model

If you want to print out something that does not exist anywhere, you will need to use software yourself to develop a new model. Fortunately, many software packages are available that make developing particular types of models as simple as possible. This section helps you think about what software package you might want to learn about, if you do not already use one.

Using a CAD Program

Most CAD programs will either save a file as STL directly or offer an option to "export to" STL. Which CAD program is the right one for the job? This section describes commonly used programs which range in price from open source and/or free to quite expensive. The programs also vary in the steepness of their learning curves. In general, the more powerful the program, the longer it takes to be reasonably proficient in its use.

Some programs have the user write computer-code–like instructions, whereas others require a lot of mouse use and more of an artistic bent. This is a quick overview of the available options; for the most part, the open source programs offer extensive documentation available for free download. The proprietary software programs typically offer training or have help available.

The descriptions here assume that the development of a model is separate from the preparation of that model for 3D printing in a slicing program. Some 3D printer companies are beginning to develop integrated programs that combine all these steps; those programs are beyond the scope of this book. Most of these proprietary integrated systems also allow importing STL files created by other programs or from databases.

■ **Caution** Some software packages are geared toward creating models meant to be viewed on a computer or theater screen (called *3D rendering*). A "3D" movie normally does not contain the parts of the model that you do not see on the screen at that moment. Various tricks exploit the way your eyes perceive 3D and fool you into thinking you are seeing a 3D image when really all you are seeing is two offset versions of a 2D image. If you are at a 3D movie looking at a 3D stereo image of the north side of a tree, that side was generated in a computer. The south side of the tree, the underside of the trunk, and some of the top, east, and west sides are not needed for the movie viewer to see the tree in 3D. However, all of that *is* needed for printing an object. Be sure the software you are looking into can export an STL file or a format that can be converted into STL.

Options for Getting Started Quickly

If you want to go from "zero to plastic" as soon as possible, you might try Tinkercad (`www.tinkercad.com`) and OpenSCAD (`www.openscad.org`), both of which are free. Tinkercad requires registration; OpenSCAD is open source. Both have example files available that you can play with and use as guidelines for your own first project.

Tinkercad: Drag and Drop

If you want to use something simple that requires no programming knowledge at all, you will like Tinkercad. Tinkercad is a member of Autodesk's suite of 3D printing productivity tools. The program is free as of this writing, although it requires the user to register. Tinkercad is a purely drag-and-drop program that supplies a lot of simple shapes such as rectangular solids, spheres, cylinders, 3-dimensional letters of the alphabet, numbers, and so on. Printable objects are created by assembling them out of these standard virtual pieces.

www.it-ebooks.info

Tinkercad requires a good Internet connection because the program is entirely cloud-based and frequently saves incrementally. If several people are using it on one wifi node, the result can be frozen screens and frustration. However, it's a great way to develop something quickly just to test the end-to-end process of creating a model, slicing it, and printing it. Figure 4-2 shows a simple heart pendant designed by the author in Tinkercad.

Figure 4-2. *Heart pendant design by the author*

Tinkercad has extensive tutorials that are arranged into bite-sized brief walkthroughs of the key features, and there are a lot of examples that others have designed and put out there for you to play with and build upon. The classic project to try first on a 3D printer is a small keychain fob decorated with 3D initials or a few hearts. Most people can do a project of that scale in an hour or so starting from zero with Tinkercad.

To get started in Tinkercad, do the following:

- Register as a user
- Open one of the public models
- Save it to STL (as of this writing, in the Design menu)
- Slice the STL file (covered in Chapter 5)

Alternatively, you can take one of the public models and alter it a bit, if the model creator allows that, and then save it to STL. If you are more ambitious, sketch out something you want to build. Remember to start small and simple—see the examples in Chapter 8 to see what makes a model "simple." Watch a few tutorials and then give it a shot. Be sure to save the object before you log out.

OpenSCAD: A CAD Programming Environment

OpenSCAD follows the opposite philosophy from Tinkercad in that it is not drag and drop at all, except for adjusting how you view the model you have developed. OpenSCAD uses a programming language very similar to C to define geometrical shapes, translations, rotations, and so on.

The program has built-in functions for most common shapes, although the names can be a little misleading. For example, all the rectangular solids are called "cubes." Figure 4-3 shows a simple file with three "cubes" assembled into a simple bridge by moving ("translating") the top and one side of the bridge away from the zero point.

www.it-ebooks.info

This structure will appear again in Chapter 5 as a test in "bridging" across gaps (Figures 5-1 and 5-7). Note that the cubes were designed to be slightly overlapping—because shapes with purely coincident faces might not have created a manifold STL.

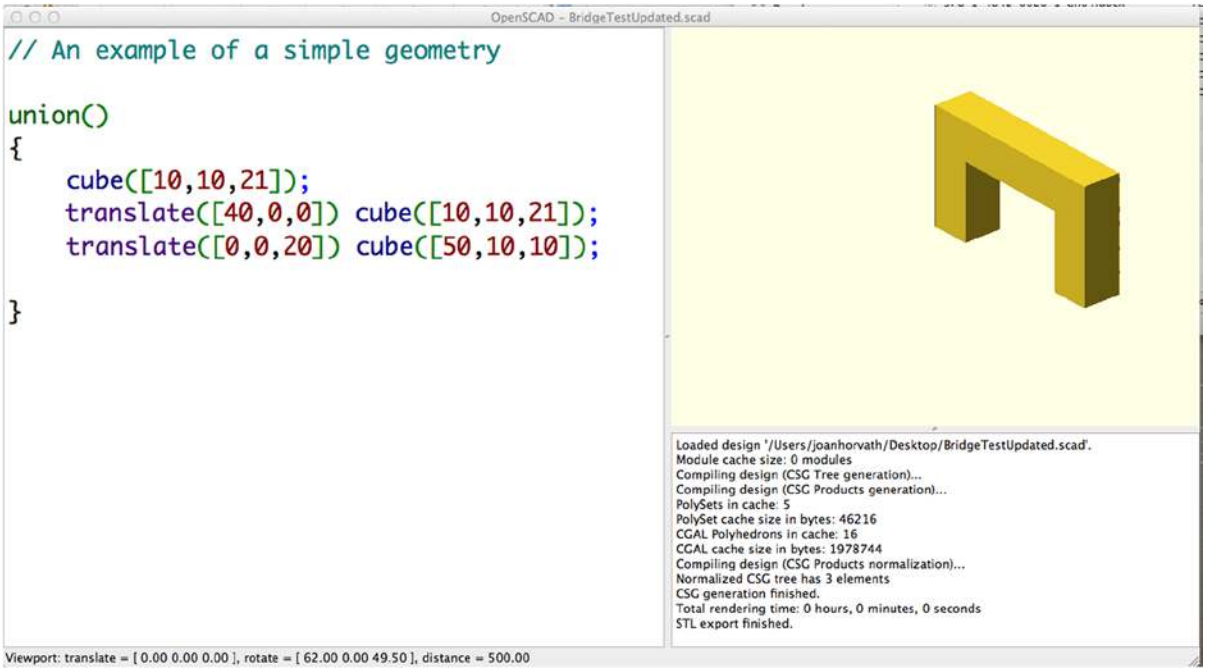

OpenSCAD - BridgeTestUpdated.scad
// An example of a simple geometry
union()
{
cube([10,10,21]);
translate([40,0,0]) cube([10,10,21]);
translate([0,0,20]) cube([50,10,10]);
}
Loaded design '/Users/joanhorvath/Desktop/BridgeTestUpdated.scad'.
Module cache size: 0 modules
Compiling design (CSG Tree generation)...
Compiling design (CSG Products generation)...
PolySets in cache: 5
PolySet cache size in bytes: 46216
CGAL Polyhedrons in cache: 16
CGAL cache size in bytes: 1978744
Compiling design (CSG Products normalization)...
Normalized CSG tree has 3 elements
CSG generation finished.
Total rendering time: 0 hours, 0 minutes, 0 seconds
STL export finished.
Viewport: translate = [0.00 0.00 0.00], rotate = [62.00 0.00 49.50], distance = 500.00

Figure 4-3. *OpenSCAD simple demonstration*

To try out a simple model in OpenSCAD, do the following:

- Click the File menu.
- Pick an example from the Example submenu (or type in the little example shown in Figure 4-3— the three lines shown are all you need).
- From the Design menu, select Compile and Render.
- If you like the looks of what you see in the 3D-rendered view, save it with the File menu. This will save the program in OpenSCAD format, not STL.
- Go to the File menu again and select Export and then STL as the file format.

You can then take the STL file and run it through a slicing program (see Chapter 5) and you will be ready to print (Chapter 6). OpenSCAD is particularly suited to modeling objects that can be built up out of geometric shapes. Complex objects are possible by starting with these basic shapes and rotating them. You can make impressive geometries with a little programming experience and the OpenSCAD manual.

Figure 4-4 shows the entirety of the OpenSCAD code for a spiral demonstration object. Figure 4-5 shows the piece as it's being printed and as it finally turned out. There are many excellent classroom applications for OpenSCAD, such as creating items to teach math. Chapter 12 explores these options further.

www.it-ebooks.info

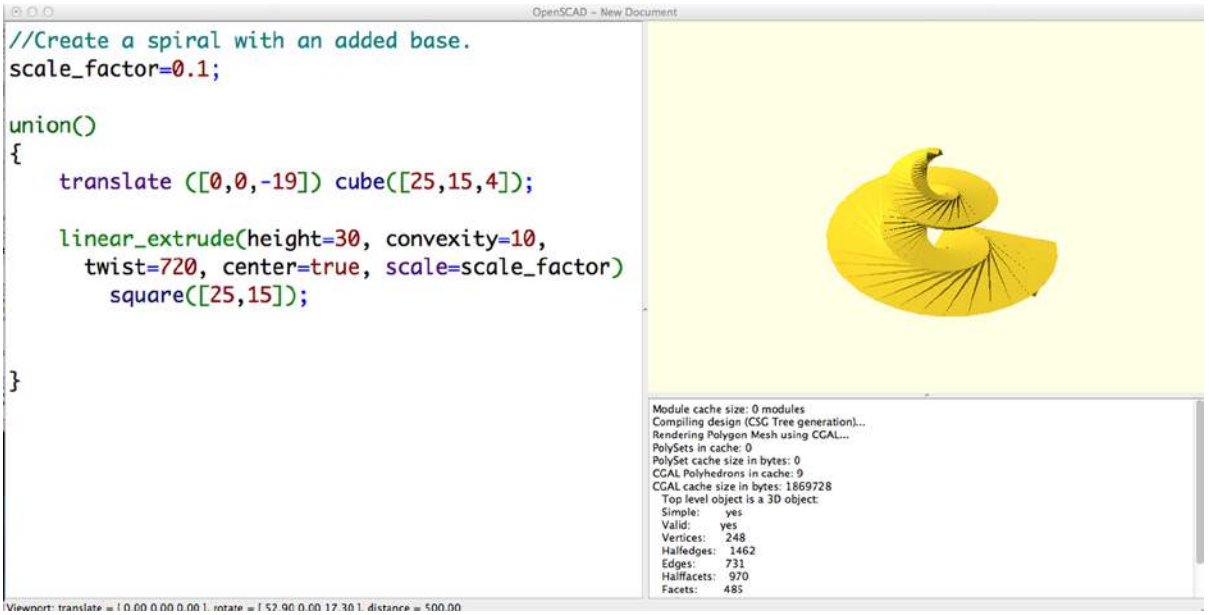


Figure 4-4. *A more complex shape*

Figure 4-5. *The spiral created from the code in Figure 4-4 as it was being printed (top) and after completion (bottom)*

www.it-ebooks.info

As an example of how much one can do with OpenSCAD, Rich Cameron (the technical reviewer for this book) built a model of an entire 3D printer in OpenSCAD, shown in Figure 4-6.

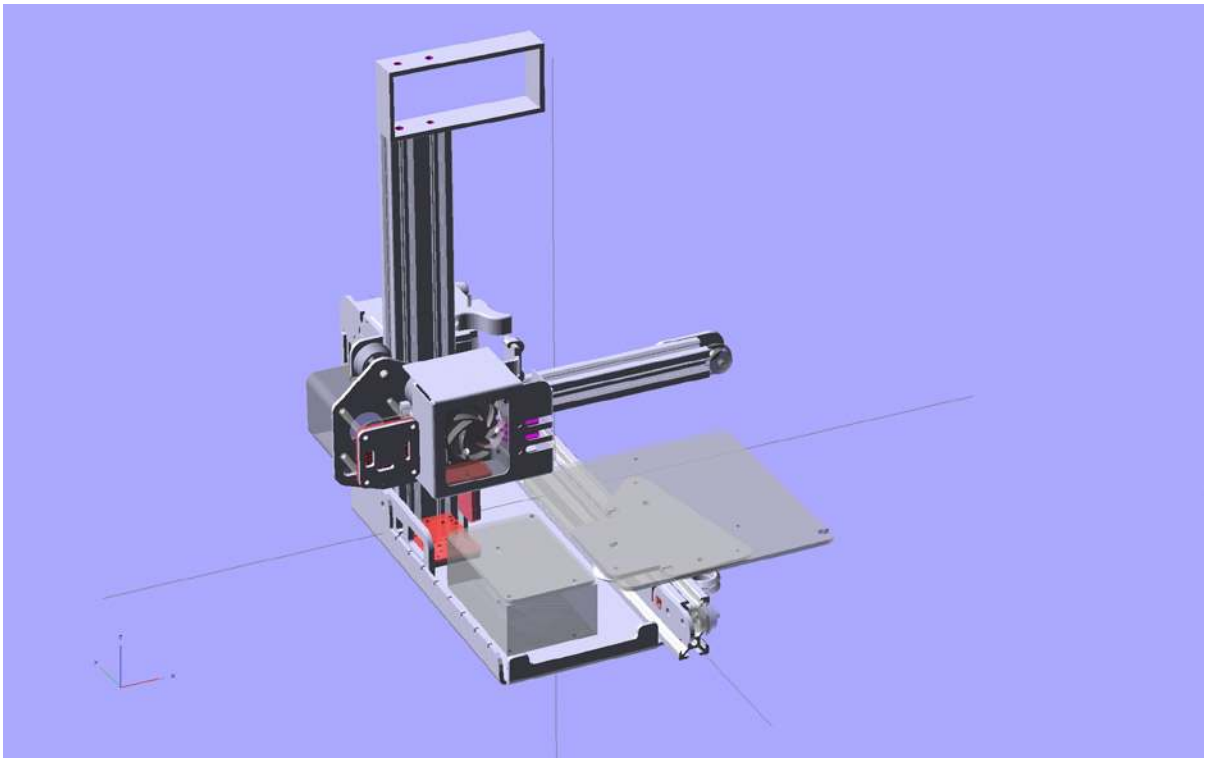


Figure 4-6. *The entire design of the Deezmaker Bukito open source printer in OpenSCAD, by Rich Cameron*

If you want to build something simple quickly and you like writing code better than using a mouse, OpenSCAD may be for you. If you have never done any programming, though, it's probably not the best choice. Typically we suggest that beginning users try both Tinkercad and OpenSCAD as two very different options for getting started, and then migrate into other more sophisticated or expensive programs after getting their feet wet.

Programs for Specific Applications

Tinkercad and OpenSCAD are great for beginners. If you are using your printer mostly as a hobbyist, in a classroom, or to make fun objects around the house, you can probably be happy for a long time with these programs. However, if you need to create professional-level sculptural models, or if you need dimensioned drawings, then these programs probably are not enough. Many, many design programs can either produce an STL file or a file that can be translated into STL. Most of these programs deserve (and in some cases have) their own book-length tutorials.

Generally speaking, you need to consider a few key attributes when selecting a design program. First, consider your own strengths: are you good at programming, or are you better at using a mouse? Do you have decent hand-eye coordination and drawing skills? How much time do you have to devote to becoming proficient, and how much design are you really going to do? A program with a short learning curve but limited capability might be okay if you are only going to make a few complicated objects, but learning a more-capable program may be worth it if those features will vastly enhance your productivity.

www.it-ebooks.info

Some software only runs on either Mac or Windows, not both. If you only have access to one or the other operating system, that may force a choice. Functionality can be different between Mac and Windows versions of a particular package, particularly in the open source world.

Next, consider budget. Free and open source software varies in its quality; documentation can be uneven or incomplete for open source software. However, it *is* free. For pricey software, research whether demonstration versions of the software are available and if so try before you buy. If you are a student, check with your school to see whether any discounts are available to you.

With all that said, programs to create models for 3D printing need to serve two broad categories of users. Engineers, architects, industrial designers, mathematicians, and similar professionals need drawings with labeled, numerical dimensions and great precision. Often they will need to integrate 3D printed parts with traditionally manufactured ones and thus will need both the ability to create a file for printing and a traditionally dimensioned, human-readable drawing. Artists may want good drawing tools that allow them to sketch freely but not require as much precision. Different tools have evolved for these respective communities, as we will see next.

Engineering and Architecture Programs

Engineers, industrial designers, and architects use 3D modeling programs oriented toward applications that require precision. The open source program FreeCAD (www.freecadweb.org) is a parametric modeling engineering-oriented program with many features that used to be available only in very expensive programs. FreeCAD runs on Mac, Windows, and Linux machines.

A common (but expensive) engineering tool is the Solidworks program from Dassault Systèmes. Solidworks is designed to create real engineering projects and as such is a good end-to-end program to go from concept to final dimensioned parts. It does take a while to become proficient in Solidworks, however, and cost can be a barrier. Solidworks is only available for Windows.

Google's Sketchup program is focused on making it easy to lay out an architectural project, including a large library of many common home fixtures from various manufacturers. Sketchup can be used more broadly, but it focuses mostly on assembling geometrical and precise models, and the resulting models may require format conversion and have problems with 3D printing.

Mathematica (www.wolfram.com/mathematica/) is a programming system that allows users to model complicated mathematical functions. Mathematica creates STL files based on user-generated mathematical models. That means it's possible to develop sophisticated mathematical models and then visualize them in physical form. This possibility has many implications, particularly for people who teach courses that use Mathematica. A natural spectrum of mathematics visualization options start with OpenSCAD and move up to Mathematica. Chapters 12 and 13 discuss classroom use of 3D printers and visualization applications.

Visual-Effects and Sculptural Programs

Visual-effects developers, animators, and similar artists develop 3D models in computer programs that are good for complex, curved, organic objects such as characters in animated films. Most of these either can export an STL file directly or employ translation utilities and procedures to take their output and turn it into STL. The commercial program Rhino, for example, exports directly into STL.

Zbrush (www.zbrush.com) is another commercial program for artists. It's a complex but very capable program that allows the user to sculpt in virtual clay. Users often abandon the mouse and draw instead on a tablet with a stylus to create very sophisticated, realistic designs of animated characters and the like.

If budget is an issue, Blender is an open source visual-effects development program, available from www.blender.org. It is extremely powerful—you can make an entire animated film with it—but has a correspondingly steep learning curve. If you're very fast with a mouse, this may be the program for you, but the program is notorious for "thinking" differently from all other programs.

www.it-ebooks.info

■ **Tip** If you are interested in creating 3D models with Blender, you might try to locate a class or, even better, a local Blender community or Meetup group. For example, the online learning site CGCookie (www.cgcookie.com) has an extensive Blender community. (Thanks to Metalnat Hayes for this tip.)

Virtual Reality Sculpting Systems

Most of the 3D modeling sculptural tools described so far have you look at a 2D computer screen and visualize in your head how the model will look in three dimensions. However, some companies are experimenting with virtual reality or augmented reality tools that allow their users to experience what they're making in 3D, or at least in an illusion of 3D.

Leonar3do (www.leonar3do.com) offers a system consisting of a *bird* (a handheld input device, shown in Figure 4-7) and sensors that detect the user's perspective on the model. To use the Leonar3do system, you put on a pair of 3D glasses and use a special 3D-enabled computer screen. You use the bird to sculpt a piece of virtual clay, which appears in 3D. The system requires a Windows computer as its interface.

Figure 4-7. *The Leonar3do bird input device. Photo courtesy of Leonar3Do International Plc*

If you do not want to use their special equipment, Leonar3do also offers a web-based version of their system at www.leopoly.com that allows you to use virtual clay with just a keyboard and normal mouse. This version works with any computer through a browser.

The Leopoly.com website also has models created by others that are available for modification and download. As of this writing, you do not have to pay anything to play with the models in the virtual sculpting area (shown in Figure 4-8), but you do need a paid subscription to download STL files to print on your own printer.

www.it-ebooks.info

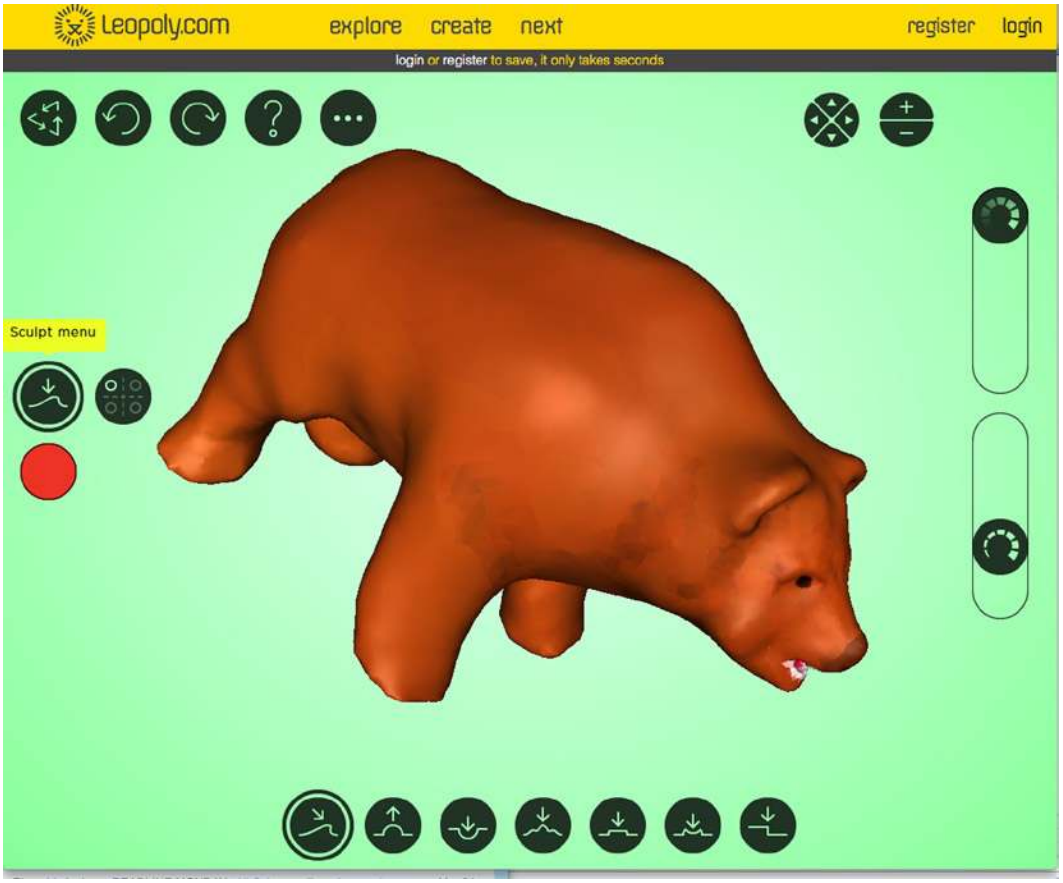


Figure 4-8. *Bear by Robin from the leopoly.com editing screen. This bear will feature prominently in Chapter 5. Image courtesy of Leonar3Do International Plc*

The bear in Figure 4-8 was created by user Robin on the `Leopoly.com` site, and we will be using it as an example in future chapters. The Leopoly editing suite attempts to mimic clay modeling tools. The controls on the right adjust the size of the instrument you are using, and the controls along the bottom offer choices in the type of tool. A lot of user-interface experimentation is going on in the community, and it will be interesting to see how many standards emerge over time.

Design Considerations

Chapter 5 covers the details you need to think about when preparing a 3D printer model for upload onto a printer. But before getting into that, let's take a step back and ask why use a 3D printer at all? What are some of the big advantages, and how can you avoid "fighting the printer" (asking it to do things it's just not meant to do)? And on the flip side, when is it a bad idea to use a 3D printer?

www.it-ebooks.info

Complexity Is Free: Hardware as a Service

One of the mantras of the 3D printer community is that *complexity is free*. Because 3D-printed parts are built up one layer at a time, it really doesn't matter whether that layer is one unbroken sheet or an intricate design. The demonstration piece in Figure 4-9 would be essentially impossible to machine, but people who know what t they are doing can print it on a low-cost consumer printer.

Figure 4-9. *This demonstration object is 3D printable without support but would be a machinist's nightmare. Design and 3D print by Diego Porqueras*

Consumer-level printers have one more strong advantage: the opportunity to iteratively design something, see how it came out, and then change the design if necessary. When that became possible in in the 1980s for computing (versus overnight batch jobs), there was a real change in kind in the nature of creating software. We all hope the same thing is about to happen for making physical things!

This phenomenon is starting to be called *hardware as a service* (an analogy to *software as a service*), and the business models are still unclear. Chapter 14 speculates on where this idea may go. Resolution and materials are likely to continue improving, and all the pictures in this book will probably look primitive to anyone reading this a few years down the road.

Speed vs. Customization

The counterargument to *complexity is free* is that complexity may matter less in 3D printing than in conventional fabrication, but complex prints may take a long time. Consumer 3D printers take a while to print anything out—it's rare for a print of any size to take less than a few hours, and prints that take a day are routine. If you're making one

www.it-ebooks.info

of something or a prototype for a mold, such a length of time may be competitive. The other option is a machinist or other professional making a prototype in a way that involves a lot of labor. But if the part is simple or you want a lot of them, a 3D-printed part is probably not the way to go. If you are happily creating injection-molded parts for something now, then a 3D-printed part is *definitely* not the way to go.

To narrow it down a bit more, consumer 3D printers may not be the best fit for your project if everything you do will require a lot of hand-finishing after the fact. You might consider using a service bureau to do one of the more industrial processes. To put it another way, only the right kind of complexity is free.

3D printing has a role for items that are by their nature one-of-a-kind (or a-few-of-a-kind) and that work well with the technology. Time will tell what the best applications are. Our sense is that one key role for 3D printing is that it makes the front of the product-development process faster. People who would have made a computer model and then created a foam-core physical mockup as two separate chores are obviously better off with a 3D printer.

Other promising markets exist in industries that make custom parts for one-of-a-kind applications (or, even better, industries that *should* operate that way but cannot do so economically at the moment). The biggest market now, though, is a somewhat intangible one: allowing people to make stuff again just because they want to and can.

Summary

In this chapter you learned about the front of the 3D printing process. The first step is creating or finding a 3D digital model of your object, which requires you to visit a website with objects available for download, 3D-scan something that already exists, or learn one of the many available 3D modeling software packages. The chapter went over the various types of software packages available for the engineer versus the artist to generate a standard (STL) 3D printing file. Chapter 5 takes that STL file through the next steps.

www.it-ebooks.info

CHAPTER 5

Slicing a 3D Model

This chapter and the next are the core of this book's explanation of the 3D printing process. 3D printers cannot use a computer model until that model is changed into commands to move around an extruder and control when that extruder is and isn't putting down material. Because most 3D printers lay up a layer at a time in some material, the first part of this process (described in this chapter) cuts the model into layers, normally referred to as *slicing*.

The first part of this chapter teaches you a little about the similarities between 3D printing and cooking and explains what a 3D printing "recipe" assumes you know. The second part introduces two common open source slicing software packages, which are the tools you will use to slice files. This chapter focuses mostly on Slic3r (www.slic3r.org); an alternative is Cura (http://software.ultimaker.com). These slicing programs are often found inside a "hosting" software package, such as the (currently) free program Repetier Host (www.repetier.com) or MatterControl (www.mattercontrol.com). These host programs provide an interface to slicing programs and also allow direct low-level access to a printer.

This chapter gives you background to do everything from a first print to a major project. Chapter 8 has several example projects to bring it all together, including some classic beginner ones to get you started.

What Is "Slicing?"

Creating an STL file (described in Chapter 4) is the first part of the 3D printing process. The next step, and the focus of this chapter, is to divide, or *slice*, the file into layers that the printer can generate. The slicing program has to take into account both the physical characteristics of the printer and the geometry of the model being printed. The final step is to make G-code file (commands to drive the printer) which we will get to in Chapter 6.

You would not expect an oven to have a big button that simply said, "BAKE." Similarly, the state of the art in consumer 3D printing is such that you need to be comfortable determining a number of different settings, like things you deal with in a recipe—materials, temperature, how fast you will push plastic out of the nozzle, and so on. The virtue of an open source printer is that, like a master chef, you can tweak your printer settings to get fantastic results. The downside is that you need to be at least a little bit of a cook to get results.

3D Printing as Cooking

Imagine you want to bake a cake. First, you might decide in general what kind of cake you want to make. You will either page around in a cookbook for ideas or create something new from your imagination; that's like creating the STL file or finding one to download from the web, as you did in Chapter 4.

Then you would get a detailed recipe for the ingredients, determine the temperature and length of time you will bake the cake, mix up the ingredients, and pour them into a pan. These actions require some experience with cooking, such as understanding what it means to grease and flour a cake pan. Knowing your oven, you might set the temperature a little differently than the recipe says or change things around to make cupcakes or to make the

www.it-ebooks.info

recipe work if you live at high altitude. This part of the process is the equivalent of slicing in 3D printing—taking your creation and figuring out what material to use, how the tools you will use will actually interact with the ingredients, and handling similar "real world" issues.

Finally, you would put the cake in the oven. You would rely on the oven controls to keep the temperature where you set it and the timer to ding at the correct time. Setting the temperature and time for baking and putting the cake in the oven is the equivalent of sending the G-code to the printer.

When the cake is done, it might get a little messed up when you take out of the pan, and you may want to add icing or do something else to it before serving. The equivalent for a 3D printer is *post-processing*. Various things you can do after the print comes off the platform are described in Chapters 9 through 11.

You can embark on making a ten-layer cake with an elaborate icing design for your next party. However, if all you have is one beat-up layer cake pan or if you have never cooked anything before, you may not get there, at least not on your first try. Similarly, you need to have a realistic idea about what types of objects you can make with your printer at your current level of sophistication and work up to grander things.

Most printers come with a set of default settings; it's best to start with those. Then use the information in this chapter to understand what those settings are doing and to take the next steps when those defaults are no longer enough. Be aware, though, that most open source printers have limited or no ability to stop you if you send commands that will print a pile of string instead of the desired object, or to recognize that the printer is having a mechanical problem. Just as you would while cooking on an unfamiliar stove with a new recipe, be sure to keep an eye on what the printer is doing, don't leave it unattended, and think through the implications of your settings. The next section goes over your software "kitchen tools" and talks about how you can use them to realize your imagined creations.

■ **Tip** If you have a hobbyist, do-it-yourself printer that does not provide settings, you may be able to find profiles for matching hardware that others have posted on open source forums and the like; check with the forums that gave you your directions. Note that a slicing software program's default settings are not necessarily the same thing as a printer's default settings, and the slicer's defaults are not likely to match your printer unless the software is developed by the printer's manufacturer. MatterControl is a bit of an exception to this, as the company is attempting to include default profiles collected from multiple printer manufacturers so that users only need to identify their printer to the software to find default settings for it.

Tools and Techniques

3D printed objects are born as computer files, and their images on a computer screen can be as fantastically complex as desired. A 3D model may look great on a computer screen, but additional structure may be necessary to make the model printable. It is possible to draw anything, but gravity and the mechanics of the printer can limit what is possible to print. For example, layers cannot be laid down in mid-air, and the model has to fit inside the volume the specific printer has available for printing.

If you have ever printed something on a regular 2D paper printer and been frustrated that only half the page printed out or that the print had purple lines across it, you can probably imagine that the equivalent types of problems become more varied and more subtle to debug when working in 3D. To avoid these problems, various techniques have been developed. We will introduce them here and then go into more depth in subsequent sections.

Before anything else matters, the model has to stick to the platform so that it can be built up layer by layer. It has to stick solidly—not peel up at the corners as it cools, and not get knocked off as subsequent layers are built on top of the first layer. Slicing software also takes into account a particular printer's platform, including how big it is, whether it is heated or not, and what type of material or covering is on the surface of the platform. Starting a print solidly is critical.

www.it-ebooks.info

Typically, a print starts with a *skirt* (a few layers printed to prime the nozzle and detect problems.) Then a print might use a *brim (*some extra material around the contact points between the print and the platform) or a *raft* (a few layers under a print) to create a solid base. A heated platform and/or tape covering the platform help with adhesion, too.

Next, consider how the model will be oriented when it prints out. If the model has pieces that would require printing in midair, some type of support has to be laid down and/or the printer has to bridge across gaps. Or perhaps the model can be printed out with a different orientation that requires less (or no) support but which introduces other design issues, such as the need to glue two halves together. Infill and support create the structure for an object as it builds up, and we talk about how all these interact later in this chapter.

Finally, the printer's design, the properties of the material, and the model geometry all affect the slicing settings in one way or another.

Starting a Print and Getting a Model to Stick to the Platform

One of the challenges with a 3D printer is getting the model to stick to the platform. Sometimes a model has a relatively small contact area with the platform, and when the extruder lays down the next layer it knocks the model loose. When that happens, the subsequent layers go in random places as the structure gets knocked around. The resulting mess is typically called "printing hair" (in polite company, anyway!) There are few worse feelings than smugly demonstrating a 3D printer to your friends and then noticing that your model is being merrily dragged around the platform, trailing strands of filament. Techniques to prevent such bad hair days follow.

Brims

A *brim* is a first layer that is larger in extent (like a hat brim) than, strictly speaking, the object's first layer needs to be. A brim usually is specified in terms of width away from the object. A few millimeters usually make a big difference. Figure 5-1 shows a brim stabilizing a print.

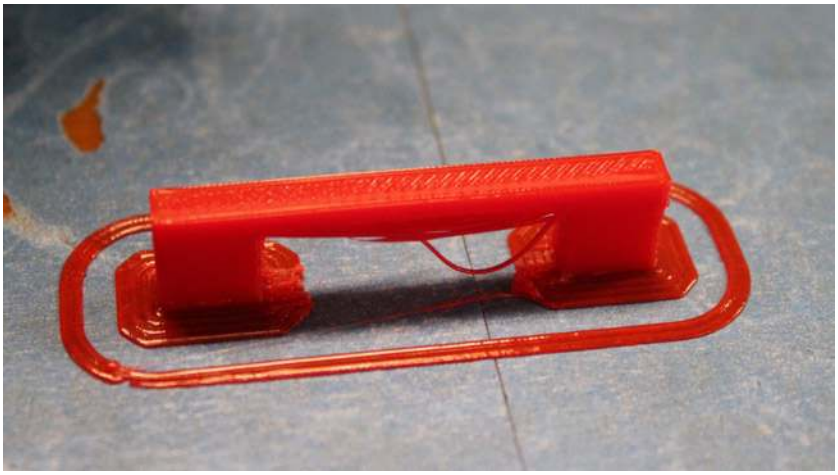


Figure 5-1. *A brim and skirt (the brim is the part attached to the feet of the bridge). This print attempted to bridge a little too aggressively (see later section on bridging)*

www.it-ebooks.info

■ **Note** Experts often make the first layer of a print a lot thicker than subsequent layers or lay down several thick layers to be sure the print sticks. A few thick layers plus a brim can make it a lot more likely a print with a small contact area will survive to the end. As of this writing, only Slic3r supports printing the first layer (not a raft) with wider lines than the subsequent layers, though some other slicing programs can change the height of the first layer. Without the ability to increase extrusion width, it is sometimes counterintuitively better to print the first layer thinner so that the ratio of width over thickness (W/T) is higher, as it is this value that has the most to do with platform adhesion. A thicker first layer with the same extrusion width will have a lower W/T ratio, which weakens adhesion, but a thinner first layer is more sensitive to platforms that are not perfectly smooth, flat, and at the perfect distance from the nozzle. This is why some users use a thicker first layer to strike a balance between adhesion strength and uneven platforms.

Skirts

A *skirt* is a few loops of filament laid down at the beginning of a print that outlines all the objects being printed at a given time and shows the maximum size of the first layer of the print. A skirt can solve several problems that might be encountered at the very start of a print.

It is possible to print more than one thing at a time on a 3D printer's platform. The programs for arranging the objects for a print run show you where the prints will be positioned relative to each other. However, it is always possible to create something that would wind up too big to print, since the (virtual) version can be hanging off the platform. When the skirt is drawn around all the objects that you are planning on printing, it allows you to quickly see whether there are any problems.

Also, if the color of the filament is different from that in the previous project you printed, it is good to print something away from your object first so that any material of a different color that is still in the nozzle is melted out before starting to print the main object. Generally, a skirt allows the printer to finish priming the extruder with filament before the main object starts printing.

Figure 5-2 shows a skirt on a platform. The skirt in Figure 5-2 tells you that the print will cover about 2/3 of the platform (the area surrounded by the skirt.)

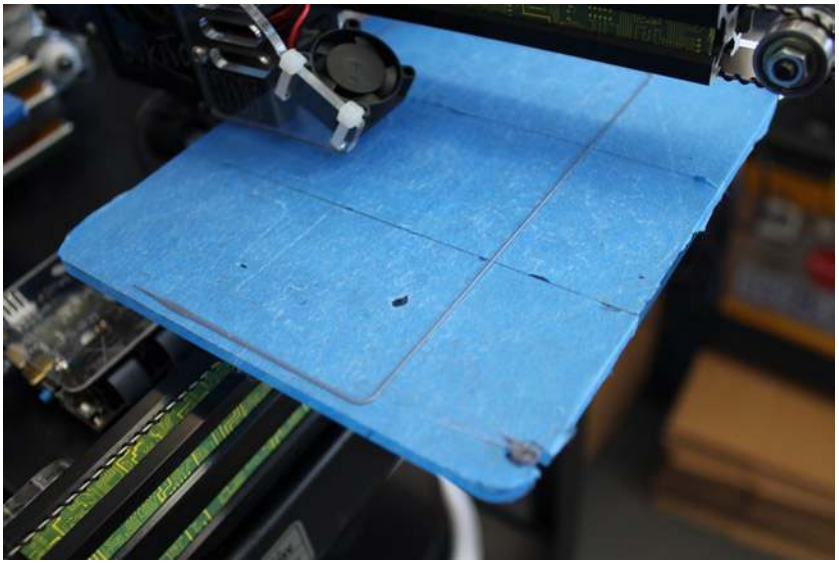


Figure 5-2. *A skirt is laid down at the beginning of a print on a platform covered with blue tape*

www.it-ebooks.info

■ **Tip** If the skirt falls off the edge of the platform somewhere, you can stop the print right away without wasting filament. Always watch the first few minutes of a print carefully. A skirt is not perfect insurance, though. If an upper layer is bigger and overhangs, the skirt will not show that.

The skirt is usually a few millimeters away from the location on the platform where the first layer of the main object being printed will reside. By the time a few loops are done, any previous filament should also be flushed out of the nozzle. Most programs allow the user to specify both the distance that the skirt is from the main model and the number of loops constituting the skirt.

■ **Tip** Add a few loops to the skirt when you change to a light-colored filament after printing a previous print with a dark filament. Doing so clears out the nozzle so there will not be any mixing of colors and resulting staining of your print.

Rafts

When you look at the lists of settings in a slicing program you may see options for a raft. A *raft* (in the sense of the word like something a shipwreck victim would make) is a few layers of support material underneath a print. In the early days of 3D printing, when beds were often uneven and there were no heated platforms, rafts could help prints stick better. This practice has largely gone out of favor since a good first layer and perhaps a brim are a better combination on a modern printer.

Heated Platforms, Tape, and Other Sticky Stuff

Another key factor in keeping the model firmly attached to the platform is the surface of the platform itself. Depending on the model of 3D printer and the filament, there are a variety of ways to ensure that the first layer of the print does not peel off.

The first consideration is whether or not a printer has a heated platform. Some materials (such as acrylonitrile butadiene styrene ABS) require a heated platform. (See Chapter 7 for details and Table 7-1 in particular for recommended temperatures for different materials.) Otherwise, prints will tend to contract as they cool and "potato chip" up from the platform as the lower layers cool and new, hot layers are placed on top. Heated platforms typically are covered with heat-resistant tape (such as Kapton tape) that can be replaced as the surface gets a little beat up from users scraping off models. Some manufacturers suggest you print on bare glass, supply glue sticks to rub on the platform, or suggest spraying on hairspray.

Machines intended to print primarily polylactic acid (PLA) plastic do not require heated platforms. PLA can print just fine on a room-temperature platform with an appropriate surface. Consumer printers often recommend covering unheated platforms with blue painter's masking tape (in particular, 3M Scotch Blue brand) to get a good solid base for PLA models while still enabling them to be pried off reasonably easily. The tape should be put on as smoothly and evenly as possible. Figure 5-2 shows what blue tape on a platform looks like in real life—it gets a bit battered and needs to be taken off and reapplied from time to time. Otherwise, a rough platform surface will be molded into the first layer of every print.

■ **Caution** If you have an unheated platform, set the platform temperature in the slicing software to 0 degrees. Otherwise, some slicing programs may generate G-code to wait for the platform temperature to warm up to a particular temperature based on the filament material. If you do not have a platform heater, your printer will simply sit and wait for an event that will never occur.

www.it-ebooks.info

To print PLA on a heated platform covered with Kapton tape, the platform will need to be heated somewhat to get the PLA to stick to the Kapton (see Chapter 7 and Appendix A for details). Some manufacturers provide a glue stick or something else to rub on the platform for each print. In that case, follow the manufacturer's directions for the printer and the filament material.

■ **Tip** An artist's spatula or painter's knife (available at any art supply store) is a great tool for getting models off platforms. A fairly stiff one with a blade a few inches long can pry a big model off a platform while leaving delicate structures unharmed. Figure 6-2 shows what a painter's knife looks like.

Supporting and Orienting a Model

Most consumer 3D printers build up their models from a platform, whether the extruder is fixed and the platform drops away or the extruder head moves up and away from a platform. This means that in some cases, a print head would be laying down material in air. For example, imagine a statue with an outstretched arm. Assuming that the statue is being printed up from its base, the initial bottom layers of the arm would print into the air and fall down unless something was printed into the open space all the way up from the platform. Material printed like this is called *support*. Sometimes this problem can be minimized or eliminated altogether by printing the model in a different orientation. This section talks about these interacting considerations.

Support

In a 3D print, the first layer sticks to the platform. Then the second layer is added above that, and so on, like a brick wall. In the case of the wall, if there are no bricks under the second layer (or at least some bricks partially lapped under it), the second layer of brick will fall to the ground.

In 3D printing, the structures that prevent the equivalent problem are called *support*. The slicing process generates support automatically in some programs, and with some user control in others. In general, it is best to avoid support if possible because removing it is time-consuming and the process of pulling it off can damage the model. You will then need to remove the support mechanically (with needle-nosed pliers, a screwdriver, and ultimately tweezers or another small tool to take off the last bits).

Figure 5-3 gives you an idea of what a supported model of a bear with a rounded back looks like as it finishes printing. In the next few pages, this bear will be arranged for printing in various ways to give you options for making the printing of a given object simpler. Note that this is the same bear you saw being created back in Figure 4-6.

www.it-ebooks.info

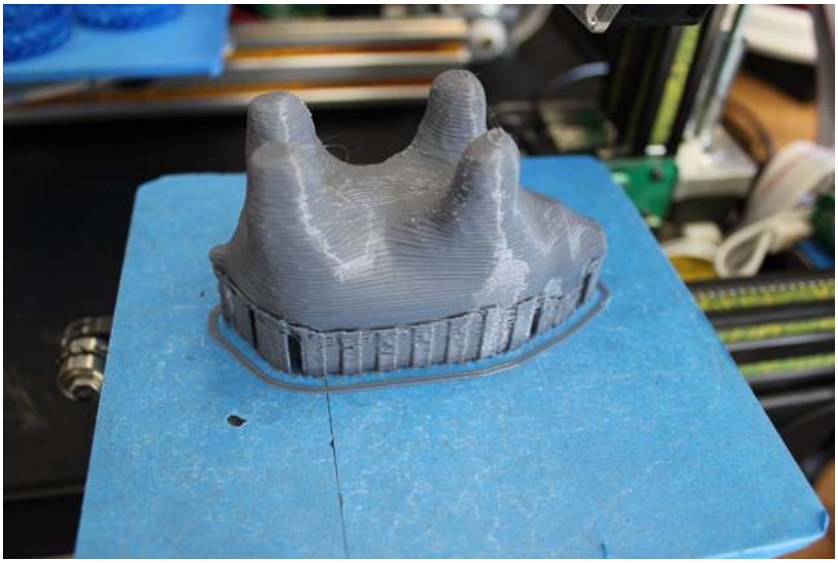


Figure 5-3. *A bear printed with support (bear from* `Leopoly.com`*, object 6439)*

Orientation

A particular model may seem to have a side that is "supposed" to be the bottom of the model. Sometimes, though, turning a model so that it lays on its side or even upside-down can increase the first-layer contact with the platform and decrease the amount of support. Particularly if you are going to be printing the object more than once, spending some time playing with the orientation of a complex model is worthwhile.

A bit of thought can sometimes also eliminate support that the slicing software would automatically create in hard-to-get-at places, like internal narrow spaces. Sometimes turning a complicated object through some arbitrary rotation—e.g., 10 degrees about the *x* axis, 15 degrees in *y*, and 90 in *z*—will result in the best situation with the least support needed.

■ **Tip** You can name a file in a way that reminds you of a good rotation for it. For example, butterfly_x80-y60-z25.stl is an STL file representing a butterfly that is best printed after rotating 80 degrees about the *x* axis, 60 about the *y*, and 25 about the *z*. Otherwise, it can be hard to keep track of the best orientation you came up with if you are going to use an STL file repeatedly.

The bear in Figure 5-3 was printed "upside down" so that the support was in the least-complex possible areas. Printing legs-up just requires a relatively small and easy-to-peel off layer of support to deal with across the bear's back. The legs have rounded bottoms that would have had almost no contact with the platform if printed pointed down, in the "normal" orientation of this object. If the legs are printed pointing upward, it's no problem. If the bear had been printed on his side or sitting on his tail, there would have been a lot of support between the legs, which would have been finicky to get out.

However, this upside down orientation will leave some support scars in a very visible spot; there are always tradeoffs. Figure 5-4 shows the scarring on top of the bear from the support after most of it has been pulled off.

www.it-ebooks.info

Figure 5-4. *The same model from Figure 5-3, showing the scarring issues*

A bit of patience and sandpaper can minimize this scarring; later chapters will talk more about post-processing. That said, there is a lot of lore about how to create the most effective support that is easy to peel off. Objects printed in PLA often have some residual bits of support that can be hard to remove and that can leave scars when the last bits are pulled off. A bit of the support grid might remain stuck on the model surface and be difficult to get off. A pair of needle-nosed pliers can grab one end of the support and get a clean pull-off started, or a screwdriver can be levered under the edge of the support to try and pull it off cleanly. Strong tweezers can be used to pick off the last bits. Various slicing programs have recently started concentrating on developing better break-away support algorithms, particularly for PLA.

■ **Tip** Support usually comes off a model printed in ABS more readily than the same support would in PLA.

Printers that only have one extruder head print support in the same material as the rest of the model. Printers that have multiple extruders can lay down support in another color to make it easier to see small areas of support and then pick them off (although one could argue that this is a bad idea because any support you fail to pick off will be more visible.) Even better, a dual extruder printer can use one of its extruders to lay down a dissolvable filament. Chapter 7 discusses the options for this type of filament and the processes used to dissolve various types.

■ **Tip** Try to avoid support in tight spaces where it is difficult to pick out, or deep inside a model. If possible, put the support on a smooth surface where it will peel off. Try to have the support attached in the least-visible possible place.

Avoiding Support by Cutting a Model into Pieces

For an object with a complex surface that requires support, sometimes you can cut the object into two or more pieces and print the pieces cut-side-down and then glue the parts together later. Some CAD programs have tools to make this sort of cut. If the program you are using does not, there are a few free or open source programs that allow the user to rotate an object around all three axes and then make a cut along a resulting convenient axis. Because this is a rapidly-evolving area, search online for “cutting STL files free software.” By the time you read this, some slicing

www.it-ebooks.info

software may have incorporated cutting as well to save you a step. Often printed support can be avoided entirely with one judicious cut. The result of taking the bear printed in Figures 5-3 and 5-4 with support and cutting it in half instead is shown in Figure 5-5. There is no orientation that allows the bear to print without support otherwise.

Figure 5-5. *The same bear does not require support after being sliced in half, but the halves will have to be glued together*

This technique is often useful too if the 3D printed model is being used to make a mold. (Chapter 9 discusses this technique in more detail.) This technique does have its own issues, though. For example, if your platform isn't very flat, or if the first layer cups up a bit, the two halves may have a gap.

■ **Tip** Some slicing programs allow you to set a different horizontal spacing for support material near and far away from the surface being supported. Set a much smaller spacing near the surface so that the support along the interface with the primary model is strong and can pull off easily. For example, the Slic3r program has a setting for spacing of support interface layers closer and farther from the object being printed to allow this. (Thanks to Rich Cameron for this Tip.)

Effects of Layer Height

3D printers print all of one layer in one plane parallel to the build platform and then step up and do the next layer. In some cases, the extruder head moves upward higher above a platform after completing each layer, or the extruder may be fixed and the build platform drops down a step at a time. Usually the two axes in the plane of the platform are referred to as *x* and *y*, and the vertical axis is the *z*-axis. *Layer height* is defined as the thickness of the material in each step up of the *z*-axis.

An extruder nozzle has a fixed diameter (like a garden hose), so a set width "rope" of material will come out of that nozzle, typically slightly wider than the nozzle diameter (because the material expands slightly as it emerges from the nozzle). (See Chapter 2's section on extruder design.)

www.it-ebooks.info

An extruder never lays down a line of filament with a perfectly round cross-section. Typically the molten filament expands a bit as it leaves the nozzle. Then the bottom of the layer flattens when it is pushed on top of the previous layer. Otherwise, it would not have enough contact to adhere to the previous layer. The top of the layer also flattens when the end of the nozzle (as it lays down the next layer) presses down on it. Thus each layer put down will have a squashed or flattened oval (flat on top and bottom) cross-section, narrowest in the *z* direction.

The filament width and the precision of the filament's diameter also drive the feed rate. Counterintuitively, a smaller filament might result in a higher net flow out of the nozzle because it causes less backpressure. The slicing programs take into account the requested speed of extrusion and figure this out without user intervention.

As the layer height diminishes, the flattened part becomes larger relative to the curved outer part of the layer. Figure 5-6 illustrates this somewhat counterintuitive result. These squashed layers make the surface appear smoother in the *z* direction than it would be with stacked round cross-section layers. In other words, the radius of curvature of the rounded "ends" of the layer becomes smaller as the layers get thinner. As the layers trend toward (unachievable!) infinitely thin layers, the outer surface approaches the ideal intended perfectly smooth surface. In practice, though, the ideal surface line runs through the rounded ends of the squashed layer. The faint gray box around the layers in Figure 5-6 is this ideal surface.

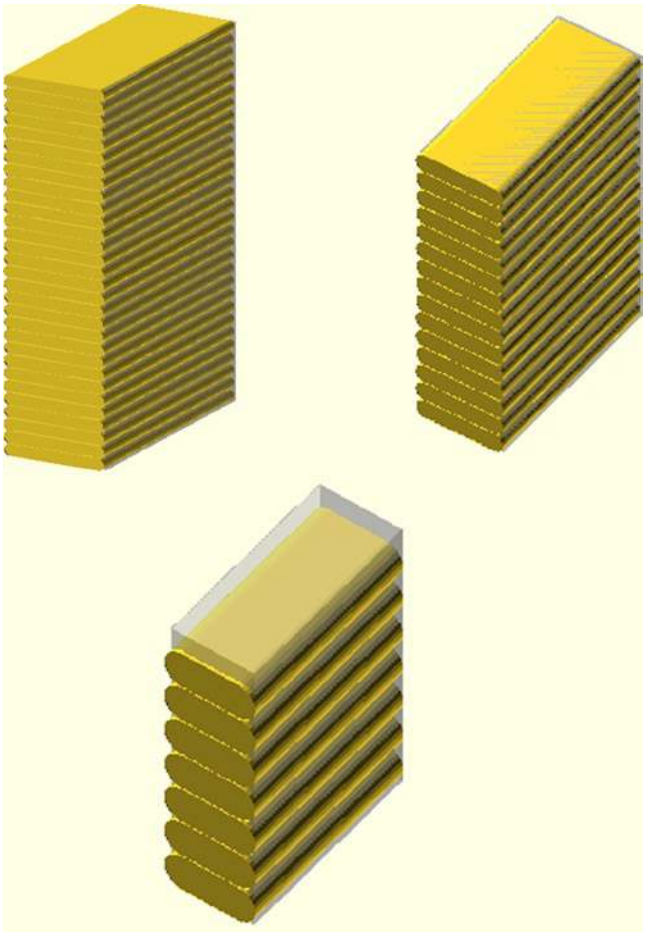


Figure 5-6. *Effect of layer height on single fused filament cross-section layer heights of 0.05 mm, 0.1 mm, and 0.2 mm. (Screen capture from an OpenSCAD simulation by Rich Cameron.)*

www.it-ebooks.info

■ **Tip** If you know the basic step size of your printer's *z* motor (frequently 5 microns, or 0.05 mm), using a layer size that is an even multiple of that step size will give the best results. If you have a 5-micron stepper motor, a 0.1 mm step should work very smoothly, but a 0.11 step may not. M8x1.25mm-pitch (6.25-micron full-step) and M5x.8mm-pitch (4-micron full-step) are more common values for reprap-style machines. (Thanks to Rich Cameron for this Tip.)

Thinner layers in the vertical (*z*) direction result in wider, flatter lines in the planes parallel to the build platform. This may mean a smoother top and bottom surface. In the real world, imperfections creep in that can cause issues and rougher vertical surfaces than would theoretically be possible. Although some of them are inherent in the design tradeoffs made by manufacturers of a particular machine (and thus beyond the ability of a user to fix), taking some preventative steps can pay off in a better print. Although print quality increases with thinner layers, prints with thinner layers take longer to print.

■ **Caution** Layer height has to be less than (not equal to!) the nozzle diameter.

Speed

A printer lays down material at a particular flow rate. For a fixed nozzle, the speed at which the printer can lay down material is set by how fast the extruder moves while printing. Slicing programs typically allow users to set various different standard speeds (for printing perimeters, support, and infill, for example). Printer manufacturers typically suggest settings for these speeds, but different types of prints might work better with some adjustments. See the case studies in Chapter 8 for some examples of adjustment of speed as a function of the type of object and filament in use.

Managing Internal Open Space

Just as there is open space around the outside of a model (like the statue's outstretched arm mentioned earlier) similar problems arise inside a model or in space enclosed by a model. Imagine a closed box: it would need some sort of support to run between the top and bottom. This support is called *infill*. Sometimes it is not necessary to have infill everywhere, and you can get away with just stringing filament across (usually) small gaps, a process called *bridging*. This section gives you some ideas about the design issues that arise with this internal support.

Bridging

It is possible to bridge across open areas in a model without support if the open area is not too wide (say, under 20 to 30 mm.) There are several schools of thought about the best settings to use when bridging across a gap. On the one hand, having the printer move more slowly than usual while trying to increase filament flow rate slightly may result in the bridge sagging a little. Conversely, having the printer move faster and pushing out less may mean the filament will not stretch enough to cross the open area and will break. Finding an optimum between the two requires some experimentation with your printer.

Slicing programs will usually allow setting a speed specifically for bridging. For example, on Deezmaker printers, it is recommended that bridges be laid down at about 15% of the speed used for the majority of the model. There is also a slicing-software setting for how much more material to try and push out of the nozzle (versus the default calculation made based on how fast the extruder is moving and the nozzle diameter). Defaulting this setting to the rate the slicing program creates based on optimum volume is a good place to start.

www.it-ebooks.info

In Figure 5-7 you can see what happens if you take a bridge a bit too far. The area bridged is 30 mm (or a little over an inch), which is a fairly aggressive distance to bridge. If you are bridging over an area that will not be visible, the distance may not matter.

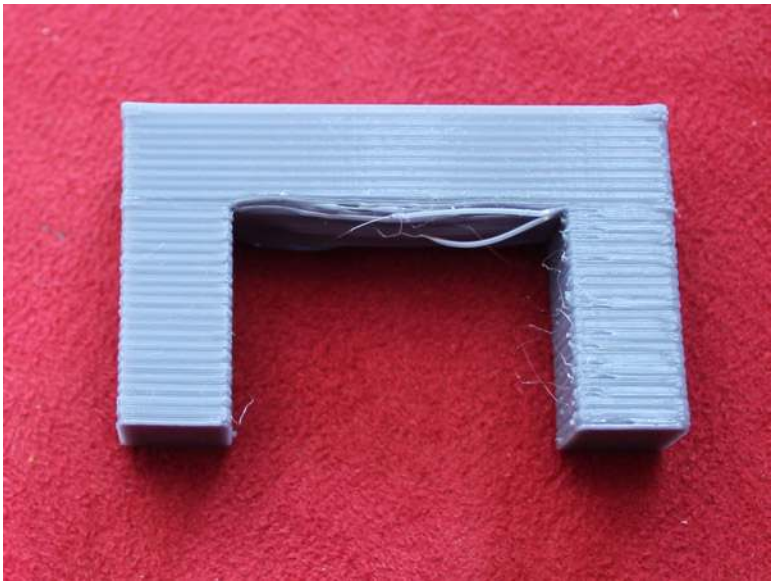


Figure 5-7. *A bridge taken a little too far for the materials and settings*

Another way to get around bridging is to terrace or arc under the bridged area so that the printer is in fact just climbing a 45-degree (or shallower) slope underneath. An overhang climbing at about a 45-degree angle is about the limit that can be printed without support. However, sometimes a steeper slope will work; a bit of experimentation is often worthwhile to avoid needing to use support, particularly in a complex structure.

Perimeters

When an STL file is created, the triangles create a surface of the printable object. This outer surface is then partially filled in to make the object stronger and to create a base for the next layer. The outer surface defined by the STL file is called the *shell*. The material that the slicing software will create for this interior support is called *infill*.

Each layer of the shell is called a *perimeter*. The perimeter can be as little as one pass of the extruder thick or as many as specified. Two is typically a good number. The thickness of this perimeter will vary depending on the extruder diameter and the layer thickness (see discussion of this in the previous section).

Infill

Users of 3D printers do not usually want to create solid objects, because that uses a lot of filament. However, typically objects can't be hollow, either, because upper layers would be printed in air. (Exceptions to this are discussed later in this chapter and in Chapter 8.) As a result, most slicing software creates internal support called *infill* inside the solid surfaces of an object to minimize filament use (as well as to make the print faster). Figure 5-8 shows some of the common types of infill. Another purpose of infill, and possibly the most important one, is to control shrinkage. Infill patterns are sparse enough to stretch axially as they shrink radially so that they don't pull the perimeters inward as

www.it-ebooks.info

they cool and shrink. This can make 3D-printed parts maintain dimensional accuracy much better than injection molded parts, which have to be designed with a significantly different size and shape from the final part in order to turn out the way the designer intends after shrinkage.

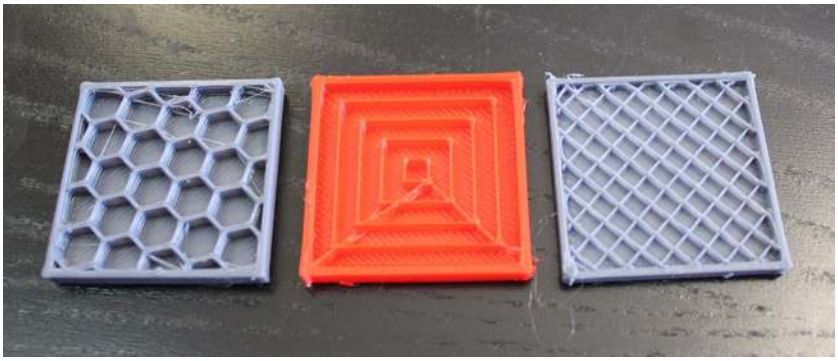


Figure 5-8. *Different types of frequently used infill: honeycomb, concentric, and rectilinear*

Print infill is usually specified in terms of percentage fill. The samples in Figure 5-8 were made with 12% infill, which means that 12% of the interior volume of the object will be occupied by material and 88% will be open. (This percentage does not include the outer perimeter of the print.) You can also specify the pattern of the infill. The commonest one is a honeycomb structure, which is a strong structure that does not require a lot of material, as bees figured out a long time ago.

The choice of infill is determined by how strong the object has to be (and in what direction it needs to be strong). The size of the object can affect selections of infill; if the object is really tiny, a high percentage infill may be appropriate so that there is enough material to make the part sturdy.

Details, Details: Retraction

One of the big advantages of 3D printing is that complex shapes that might be impossible to create via traditional machining can often be made very easily. But there are some features that are challenging to 3D print—with a consumer printer, anyway. For example, one thing that can be difficult to print is a surface with a lot of fine detail or holes in the *x*-*y* plane, like a piece of lace. Imagine a part with a small (1 mm or so diameter) gap in it in the *x*-*y* plane. To "leave out" that hole, the extruder needs to pump out material right up to the edge of the hole, stop extruding, and start up again on the other side. This is referred to as *retraction*.

Typically the smallest feature size that can be reliably printed in the *x*-*y* plane is quite a bit bigger than the smallest *z*-direction layer the printer can support because of the limitations on retraction (see Chapter 2's discussion of extruders and retraction). A printer that can comfortably print a 20-micron layer typically can only create a distinct feature (a hole, or a small raised part) on the 1000 micron (1 mm) or so scale because of this practical limitation.

Thus a print may be very smooth on the tens of micron scale for a good-quality, well-tuned consumer printer, but the smallest clean holes may be a factor of ten or a hundred bigger. When retraction doesn't keep up, the print may have fine hairs of filament scattered across the spaces that were supposed to be open; this is referred to as *stringing* (Chapter 11 discusses how to alleviate stringing).

Retraction is typically handled as an automatic feature in slicing software with some limited user control. For example, Slic3r has a check box to retract only when crossing a perimeter. This is a way to avoid retracting if printing sparse or complex infill might otherwise require it. It doesn't matter if infill strings a bit, because it will only be visible inside the model when the model is complete. Doing a lot of retraction can wear on the filament in some printer configurations and slows down the printing process, so avoiding it where possible is a big plus.

www.it-ebooks.info

Getting Started: How to Slice an Object

So you have gotten an STL file somehow and you have thought about how to print it, given everything in this chapter so far. Now what? First, you will want to download an open source slicing program.

This section discusses Slic3r in its embodiment as a program wrapped inside the Repetier Host hosting program, but other available programs have similar capabilities.

Your printer's manufacturer may also have a list of suggested software and settings; you should start there as a base. Otherwise, the following will get you started.

■ **Note** This book does not for the most part use screenshots of open source programs, because the programs change frequently. On top of that, most open source programs have Windows, Mac, and Linux versions, and typically these versions have different interfaces. Instead, this book describes the general steps necessary to walk through the software and assumes that you will be able to work with the program's manual for the rest.

Slicing Programs: Slic3r

The Slic3r program is a free, open source slicing program that handles most of the issues discussed in this chapter. Slic3r (or a program like it) takes an STL file (see Chapter 4) and, based on settings input by the user, creates commands that can be executed by the printer. These commands are in a language called *G-code*. G-code is a very old command language that has been around since the 1950s to control traditional computer-driven machine tools; Chapter 6 covers G-code in detail.

Slic3r (downloadable at www.slic3r.org) can be accessed either as a freestanding program or embedded in other free "host" programs, such as Repetier Host (www.repetier.com) or MatterControl (www.mattercontrol.com).

Downloading the Programs

To get started with Slic3r, download Repetier Host from the link just given, which will also download Slic3r as an embedded program. Or you can also download MatterControl, which has embedded both the Slic3r and Cura slicing programs as well as its own slicer, MatterSlice. This section describes the Repetier Host implementation, but the two are similar in philosophy. Chapter 8 illustrates the end-to-end development process with screen shots from MatterControl.

Getting Settings into Your Printer

Slic3r requires three types of settings: *printer settings, print settings*, and *filament settings.* If you get basic settings pre-created from your manufacturer, there will be three file folders available for download with instructions about how to get them into Slic3r.

For a typical example of how to move manufacturer-supplied settings into a place where Slic3r can find them, go to www.bukobot.com, click on one of the printer models, and then click Settings. The text there will have a current description of how one of the slicing programs will accept settings and a settings file for that particular machine. (Do not assume that those settings will necessarily be good for your machine, though, if you have a different one.) This process may be simplified soon.

www.it-ebooks.info

Assuming that your manufacturer does indeed provide files for you, follow its directions to load the files into Slic3r or the slicing software recommended. It is likely that there will be three types of settings:

- *Printer settings*: Relate to the hardware of the machine; should be available from the manufacturer (baud rate of connections, recommended head speeds, and so on)
- *Print settings*: Relate mostly to the geometry of the object being printed, but also to the machine's and filament's limitations (the types of things covered in this chapter)
- *Filament settings*: Relate mostly to the material you are using (see Chapter 7)

If you do not have any other options, Appendix A provides a list of typical settings for a Deezmaker Bukobot 3D printer. It will at least give you some numbers to get started and give you a sense of reasonable numbers; you can use a combination of experimentation and the information in this chapter to see what works for you.

■ **Tip** 3D printing software typically uses metric units. Get comfortable with millimeters (mm); 25.4 mm = 1 inch. If you bring an STL file into the object placement area and nothing seems to be there, try scaling by 25.4; it may have been made in inches and been so tiny on the platform that it was invisible.

Slicing a Model using Slic3r in Repetier Host

This section gives general instructions about the workflow in the Repetier Host program as of this writing, with a focus on the Mac version. Future versions and other hosting programs may vary in detail, but the broad steps will likely be the same. Here are the steps for running the Mac version of Slic3r.

The Windows and Linux versions will vary in detail, but these steps will give you enough of an idea that you should be able to deduce how your version operates.

- First, download the programs.
- Download settings files from your manufacturer as described in the "Getting Settings into Your Printer" section. Open Repetier Host and click the Slic3r link or tab so that Slic3r opens. Or, if your manufacturer did not supply settings, follow the configuration wizard or click Configure and type in settings.
- Once you have settings typed in or read in, close Slic3r and Repetier Host and restart them. This will enable Slic3r to find the settings folders, if any, on its next opening. Slic3r also has a decent manual at `http://slic3r.org`.
- Put Repetier Host into Object Placement mode by clicking the appropriate tab.
- Click the Add STL File tab. Locate an STL file you want to print and load it in.
- If it overflows the platform, scale it down. If it is invisible, try scaling it up by 25.4 (it might have been in inches).
- Will the STL file need support in its current orientation? Is there an orientation in which it would not? If so rotate it.
- Do you want to slice it in two (or more) pieces to avoid support? If so:
  - Use Meshlab or another program (see Chapter 4) to slice it up.
  - Then delete the original STL file and import the pieces.

www.it-ebooks.info

    - To arrange pieces on the bed, select each STL file from the list and then select the tool that looks like a little truck. That will let you drag pieces around.
    - You might need to rotate the pieces to get them all at the best angle. Or, if the pieces are big, you might want to print them one at a time.
- Select all the objects and use the Drop Object button to be sure all the objects are on the platform and not hanging in the air above it.
- Go to the Slic3r tab in Repetier Host. Use the Configure button to see the settings details. Be sure you are happy with your settings:
- Does the model need support? If so, be sure those settings are set appropriately.
- Do you want a rough print or a good one? Set your layer height accordingly.
- Consider any other issue for your print that might require changing a setting.
- Save the new settings, if any. Note that Printer, Print, and Filament settings all need to be saved separately.
- Once you have changed settings, be sure the three pulldown menus (Printer, Filament, and Print) are all using the group of settings you intended.

■ **Caution** To change any of the settings for Slic3r, select the Slic3r tab in Repetier Host, select Configure and then be sure the pulldown menu is set to the group of settings (sometimes called a *profile*) that you want to change. If you exit without saving, nothing will be changed. It is usually wise to save changes to a new name until you are sure you like the new ones.

- Now click the area that says "Slice with Slic3r" and look at the messages scrolling in the bottom of the screen. Are you getting warnings about a non-manifold model or a hole at some location? If so, either kill Slic3r and run the model through a program such as Meshlab (Chapter 4) to "clean" it or let Slic3r try to fix it. If you go the latter route, look carefully at the rendered G-code to be sure nothing wacky happened (see next step).
- If you did not get any error messages during slicing, the program should generate a G-code file. If you are using Repetier or another host program that supports a full rendered model view, you should click on the G-code tab and see how the slicing turned out, where the support is (if any), and to detect other issues. Chapter 6 shows you how to load and run the G-code onto the printer.

Chapter 8 walks you through the design considerations and slicing settings for three different types of objects: a very simple one, one that requires support, and something that is built up in a spiral (like a vase.) Appendix A has a table of Slic3r settings for these examples on one typical consumer printer. If how this all fits together is unclear, you may want to jump ahead and browse those examples a bit.

www.it-ebooks.info

Alternative Hosting and Slicing Programs

The hosting and slicing software markets are expanding rapidly in both the open-source and proprietary realms. The open source Cura program (http://software.ultimaker.com) offers less control in some ways than Slic3r, but has some algorithms that are better than Slic3r's (and less control can mean fewer pitfalls for the inexperienced.) Generally speaking, if you can become comfortable with one program, you can always adopt another later when you become more sophisticated and begin to develop more specific needs and wants.

Summary

In this chapter you learned how to create "recipes" to slice your STL file and prepare it for printing. You saw some of the key settings that slicing software uses and what their implications are for 3D printing your project. The chapter walked through how to set up and use a common open source slicing program, Slic3r, inside the Repetier Host program.

This chapter covered the middle part of the overall 3D printing workflow, bridging Chapter 4's development of a model on a computer screen and Chapter 6's hands-on interaction with the robotics of the 3D printer. Looking further forward, Chapter 7 will cover filament-related settings in more detail.

www.it-ebooks.info

CHAPTER 6

Driving Your Printer: G-code

In Chapters 4 and 5 we developed a model (an STL file) and sliced it to make it ready to print. We did not really talk much about what is in that sliced file (a *.gcode* file) and what to do with it. To carry forward the metaphor from Chapter 5, we will now turn on the oven and figure out how to actually "bake the cake."

At this point we start mechanically building parts versus creating idealized images of parts on a computer screen. This transition can lead to some surprises (and humbling experiences). The extruder and the build platform can get pretty hot, and things do not always turn out the way you would expect. Very often this will be an iterative process: you will start printing your file, discover that things are not going according to plan, and need to go back and reslice. It takes a little while to know your printer and develop some intuition—don't get discouraged!

Tip In this chapter you will read about many printer settings that can be tweaked during the process of making a 3D print work in the real world. Be methodical and change one thing at a time. Consider getting a little notebook (or making an online document) to write down what worked and what did not. Otherwise, it all blurs together after a while!

This chapter shows you how to move the sliced file (G-code) onto the printer. If you sliced your file inside one of the host programs that includes a slicer (for example, Repetier Host or MatterControl), then you can continue to work inside that host program to move the sliced file onto the printer and monitor its execution. If you used a freestanding slicing program (such as Slic3r or Cura), then you will import the sliced file into one of the host programs and continue the process from there.

This chapter covers several of the common host programs and a few different approaches to this final stage of the 3D printing process. Beyond that, sometimes you need to tell the printer what to do without the benefit of a sliced file, and this chapter shows you how to command some simple activities directly from the host program, too.

Controlling Your 3D Printer

Most open source, filament-using 3D printers are controlled with a series of commands, called *G-code*. Figure 6-1 shows how G-code flows through a typical open source printer. G-code loads onto the printer from a host computer via USB port, although some printers have other options such as reading from an SD card. The *firmware* (software running on the printer itself) then interprets the G-code one command at a time and ships it off to the printer to execute. Status information (temperatures and the like) return to the user's computer through the USB. In some other cases a G-code interpreter runs on a host computer, and control signals are sent to the printer.

www.it-ebooks.info

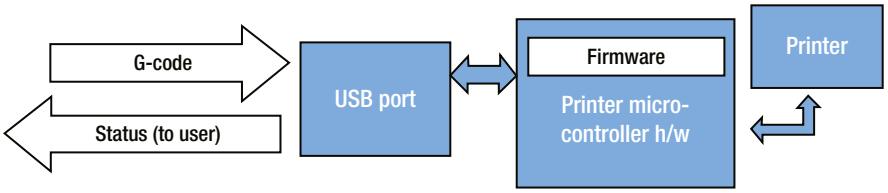


Figure 6-1. *Hardware and software architecture*

Many open source printers use Marlin firmware, which runs on Arduino-compatible microcontrollers. There is no operating system running on a microcontroller in system architectures like the Arduino. The processing hardware performs minimal command retrieval buffering and interpretation functions, and returns requested signals to the user. The shaded boxes in Figure 6-1 represent hardware; the unshaded boxes represent software and data. Although this architecture is the standard as of this writing, 32-bit ARM-based architectures may replace these lower-powered ones.

There are variations on this theme: for example, some printers can read from an SD card rather than needing to use a USB port. In that case, the user has limited ability to monitor the printer in real time.

Understanding G-code

G-code is a very old programming language originally designed to control machine tools with a computer. Its origins are in the 1950s and 1960s and it has survived this long because of its flexibility and ability to run with minimal computing power. G-code is very low-level and is typically written such that all the commands are interpreted one at a time sequentially. Typical G-code functions include commanding an extruder to heat up to a particular temperature, instructing the printer to pause until an extruder reaches a certain temperature, moving the extruder to some (x, y, z) position, and conducting similar activities.

G-code for machine tools evolved gradually, with different dialects for each tool manufacturer. A standard of sorts called RS274D stabilized in the mid-1980s. Because the computer numerically controlled (CNC) market was pretty stable when the first low-cost 3D printers came along, a lot of the early users borrowed firmware and concepts to program those machines, and so a G-code dialect for 3D printers developed.

Each line of G-code commands the printer to do some small task or to set some parameter to a value that will be used for a task later on. For example, the snippet of code in the example that follows first sets the units that the firmware will use for calculation to millimeters (`G21`). It then tells the firmware to use absolute, not relative, coordinates (`G90`) and then commands the printer to move to position (3.000, 8.111, 4.444) while extruding filament such that 0.1234 mm of filament will have extruded when the command is completed (`G1 X3.000 Y8.111 Z4.444 E0.1234`). The firmware interpolates the movements required to get from one absolute position to the next and similarly determines how to feed the filament to extrude the requested amount before the next step. Millimeters of filament moved is currently the most common unit for the E values; but this may change to a volume measurement by the time you read this book.

```
G21
G90
G1 X3.000 Y8.111 Z4.444 E0.1234
```

Not all G-codes begin with `G`. For example, codes beginning with `M` are used (with some variation among manufacturers) for other mechanical functions. `M104` is commonly used in open source printers to set the extruder temperature to a particular value. `M140` sets the temperature of heated build platforms—in this example, to 115 degrees C. `M109` waits for the temperature of the extruder to reach the specified level, and `M190` waits for the temperature of the heated platform to reach the specified temperature. An example of this sequence is shown in the following example. (Note that though the code is usually written as shown in the example, `M109` and `M190` do not need to have a temperature specified. If none is given, then the temperature that was set with `M140` and `M104` commands will be used.)

www.it-ebooks.info

■ **Tip** Each line of G-code needs to be on one line (no newlines). A semicolon on the line makes the rest of the line a comment (see the example that follows).

```
M104 S210   ;comments here
M140 S115
M109 S210
M190 S115
```

Printers with multiple extruders need to address lines of G-code to the correct extruder. This is done with a *tool change* command, `T`. For example, in the case of most open source dual-extruder printers, `T0` will select extruder 1, and `T1` will select extruder 2 (following the common computing convention of beginning to count at zero). A `T0` code will cause everything that follows to be executed on extruder 1. Some G-codes allow a `Tx` to be appended on the same line to show that just that command is for extruder `x`.

■ **Tip** A list of 3D-printer G-codes and a detailed discussion of their functions is available at `http://reprap.org/wiki/G-code`.

As you will see in the rest of this chapter, it is sometimes useful to be able to type in these low-level codes to debug possible hardware failures (such as blocked extruders, a lack of connection to the printer) or to change the G-code built by your slicing program. Sometimes it is convenient to test that the printer is working correctly with a few simple commands rather than a complex G-code file.

Using Host Programs

Slicing programs create a G-code file. However, you need to use a *host* program to send this file to a printer. Several different host programs are available. Repetier Host (`www.repetier.com`) recently ceased to be an open source program, although as of this writing it remains freely available. MatterControl (`www.mattercontrol.com`) is a newer, still-evolving open source program. Repetier and MatterControl both work on Windows, Mac, and Linux machines.

Octoprint (`www.octoprint.org`) runs on Linux computers, is open source, and is intended for low-power systems like a Raspberry Pi. (This allows the use of a Pi as a printer host instead of tying up a more-expensive computer for long prints.) Octoprint is unique in that it is web based, and so it can run over a network with a wireless-enabled Raspberry Pi physically connected to the printer.

Repetier Host

The Repetier Host program is an end-to-end hosting program that takes in a 3D model file in STL format, calls the Slic3r slicing program (see Chapter 5), and produces G-code. Repetier Host can also load the program onto the printer and display status information coming back from it in real time.

The first time you use the program, you will need to load in printing and slicing settings for your particular printer. You can either do this manually, using the wizard provided, or load in settings provided by your printer's manufacturer. If your manufacturer provides files with settings for Slic3r, follow their directions to load in the settings. If not, use the wizard and the information in Chapter 5 to come up with basic settings. You may need to close the program and open it again to see the settings.

www.it-ebooks.info

After the first time through (which may take some iterations to get going) Repetier workflow will be along the lines of the following. The program is in the process of going closed-source, and thus changes may be in the works. The Mac and Windows versions are very different from each other as well. Thus we are not providing screen shots, which likely would change by the time you read this. Instead we are trying to be descriptive enough so that you can find the relevant path through the software even if it changes quite a bit.

■ **Note** If you want to print using an SD card, see the section "Running from an SD Card" later in this chapter for details.

Chapter 5 reviews in some detail how to slice with the Slic3r program in Repetier Host. The following repeats the high points just for clarity, now that we are filling out the remaining workflow to put the G-code processing in context:

- Go into the object placement area and add an STL file or files.
    - Move around the files as needed to get them to fit. To move objects, select the object's name in the list of STL files and select the tool that looks like a little truck.
    - When you are done moving around the objects, select each object and click "Drop Object" to be sure that the object is on the build platform. Check that nothing is hanging off the platform.
- Go into the Slicer area and select the Slic3r settings appropriate to this particular STL file and filament material (see Chapters 5 and 7, respectively.)
    - As of this writing, the button is a big rectangle in the Slicer area that says "Slice with Slic3r." Click it to initiate slicing.
    - If any errors appear, see the suggestions in Chapter 5 for fixing issues like holes and non-manifold prints.
- Go to the G-code area. Take a look at the 3-dimensional model of the G-code and see if it matches what you had in mind. If not, revise your model (Chapter 4) or settings (Chapter 5).
    - You can step through your G-code as it would print by selecting "Show layer range," setting the first layer to 1 and then setting the last layer to a progressively higher number. It's a quick way to see how the piece will print.
    - If you see a lot of zigzagging lines in addition to the printed part, that is the travel—when the extruder moves from place to place without putting down any plastic. You can turn that off if it makes it hard to see the piece.
- If it looks good, then go to the Print panel.
    - Once in the Print panel, click "Connect" to connect to your printer. If it fails to connect, check the USB connector and make sure the printer is on.
    - If this is the first time you are using this computer with this printer and the physical connections seem OK but the computer is not seeing the printer, check the "Printer settings" at the top of the window (versus the "Printer" settings in the slicing window) and be sure your printer settings match the manufacturer's recommendations.

www.it-ebooks.info

    - Once you have input your manufacturer's settings for the key printer settings, and the printer is connected and turned on, do the following:
        - Try some simple commands (see the next section of this chapter) or you can click "run" to start your print job.
        - Assuming you are trying to print an object, go to the temperature view. This shows you the target and actual temperatures of the extruder and the heated platform (if your printer has one).
        - Are things heating up? If not, see Chapter 11 on troubleshooting or try some of the simpler printer commands described later in this chapter in the section "Extruder not Extruding."
        - Once the extruder and platform are up to temperature, the print should start, typically with a skirt being printed first.
        - You can watch the progress of the print in the 3D view. However, if your model is complex, this can cause crashes. It is better to leave the temperature monitor up for the long run and just to watch the actual print being created rather than an animation of it.
        - You can see how far along your print is by watching the count of layers done versus layers to go. The program gives a time estimate when it first slices the file, but the estimate usually needs to be multiplied by at least two and often more.
- Alternatively, if you have a G-code that you or someone else created previously (using Slic3r settings appropriate for your printer), you can also use the "Load G-code" function and run from that without starting from the STL file.

■ **Caution** Do not disconnect your computer from the printer while it is printing if you are using Repetier Host or MatterControl over a USB connection. You will stop the print, and there is no good way to restart.

MatterControl

The MatterControl host program is a relatively recent open source addition. The workflow description explained here is based on a beta version, so check the documentation if it seems a little off. MatterControl has the major advantage that it wraps around three slicing programs with somewhat different strengths (Slic3r, Cura, and MatterSlice) and allows you to select which one you use for slicing your file.

As with Repetier Host, the first time through you need to load in printer and slicing settings. Once you have gotten through that, the workflow goes like this:

- First, select your printer.
- Click Add to add an STL file to the queue.
- To look at the file, click it in the queue and select View.
    - In View you can rotate, view, or scale the model and display the result in various ways.
- When you are happy with how things are laid out on the platform, you can close the View window.

www.it-ebooks.info

- Click ADVANCED CONTROLS
  - Select SLICE SETTINGS and change any settings as needed (see Chapter 5 for more on these settings).
  - Pick either the Cura Engine, MatterSlice or Slic3r. Cura Engine is a particularly good choice if you have a complex print and/or difficult support to create. MatterSlice is a new slicing engine as of this writing.
- When you are happy with all your settings, connect your printer and run the job. Slicing will happen automatically, or you can export a G-code file.
- To use low-level printer controls, go to ADVANCED CONTROLS and then PRINTER CONTROLS.

Octoprint

Octoprint is a simpler hosting program than the previous two. It is designed to run on a low-compute-power Linux computer, such as a Raspberry Pi. It does not have an embedded slicing capability, because slicing is rather compute-intensive and likely to be too much for a Pi-level computer anyway.

Octoprint is meant to be accessed remotely via a web browser. It runs on the Pi (or other Linux machine) and some versions of Windows and is capable of loading a G-code file onto the Pi and thence on to the printer. It can initiate a run and has some basic (but very helpful) visualization capabilities. If you do not have an SD card reader and want to avoid tying up your computer for long periods of time during a print, a Raspberry Pi and Octoprint might be a good solution for you. It is possible to add slicing capability to Octoprint but it is not included in the default download as of this writing.

Printing a file using Octoprint requires these steps:

- Use your regular (Mac, Windows, Linux) computer to slice the file and create a G-code file. You can use Slic3r, Cura, or other programs for this, or slice inside MatterControl or Repetier Host.
- Log in to Octoprint via a web browser on your regular computer.
- Upload the G-code from your regular computer onto the Pi using Octoprint.
- Once the file is up there (be patient—loading onto a Pi can take a while), then you can connect to the printer and tell it to run.
- Be sure you have some way of seeing what the printer is doing and are able to intervene (if the Pi and printer are not sitting next to you) in case something goes wrong.

When a Print Starts

When you have successfully sliced a part to create G-code and used a host program to send it to the printer, what happens next depends on what is in the G-code and also on the printer's firmware. If your manufacturer gave you standard settings files, it is likely that there are some G-codes that are added to the beginning of every print to "home" one or more of the axes (to bring the nozzle to some known point on the platform), or these codes might be in the firmware. In either case, typically the printer will move the extruder to a predetermined starting point (usually off to one side) and will heat up the extruder and platform heater (if there is one).

After you tell the printer to run your G-code, you can watch the heaters kick in on temperature-monitoring graphs in any of the host programs mentioned previously. Once the extruder and platform reach the right temperature, the extruder will usually "drool" a little to get some filament melted before the print proper starts. Then the printer will start to print a skirt (if you specified one) and then your print.

www.it-ebooks.info

The first time you see a 3D printer making an object, it is mesmerizing. There's an in-joke in the community that the second item people print out is a chin rest so that they can watch their prints in comfort!

■ **Tip** Host programs give estimates of build times, but the real build time typically is much longer. This is because the firmware doesn't move at exactly the speeds specified in the G-code, but rather accelerates and decelerates each time it changes direction, making its average speed lower. These calculations occur in the firmware, so the host program does not know how much this will affect the print time; some hosts offer better estimates than others.

During a Print

Once a print starts successfully, there's not a lot to do except to keep an eye on it in case something goes wrong. It's not a good idea to leave a 3D printer unattended, just as you would not go too far from a turned-on stove or oven. After a while, you will be able to tell from the sounds your printer makes if all is well. 3D prints can take a long time (many hours is common), and in the beginning you might try to do small tests of new techniques and materials so you can watch the proceedings actively and intervene if the print does not go as planned.

The commonest failure is having the print come loose and slosh around. The only thing to do in that case is to kill the job (from the host program) and change some of the design to have a bigger footprint on the build platform, or perhaps print at a bit higher temperature. If a print just doesn't look right, go back to Chapter 5 and consider changing some of the slicing settings; look at Chapter 7 to see if the filament properties might be the problem; and consider Chapter 11's troubleshooting ideas if you suspect your printer. The platform may not have been adequately aligned and prepared.

When a Print Finishes Normally

When your part finishes printing, ideally the result will be a part sitting on the build platform looking just like you imagined it would. However, you still need to get the piece off the platform without breaking it. How do you get any support, brims, and so on off the part? And what should you do to be sure the printer is ready either to be turned off for the day or to print the next job?

■ **Caution** If your printer has a heated build platform, wait for it to cool down before you remove the part. Otherwise, the part (which is still a little soft) may bend or warp as you take it off or if it cools too quickly off the platform.

Getting a Part off the Build Platform

Once the print has cooled down (see the preceding Caution), sometimes you can just grasp a part firmly and snap it off the platform. Usually, though, you need a little leverage to get it started. Keeping a part firmly attached is one of the more difficult issues in 3D printing, but sometimes the pieces adhere a little too well.

Unless your manufacturer recommends another implement, a common tool to pry pieces off the build platform is one of the tools used by artists: a paint knife (shown in Figure 6-2), an artist's spatula, or a palette knife. These work well on blue and Kapton tape. Get one that is fairly stiff so that it is strong enough to move a substantial part. The exact form factor is a matter of taste and experience, but the shape in Figure 6-2 works well. Any art supply house should carry them (for example, Blick's, www.dickblick.com.) While we are talking about small handy tools to have in your kit, you should also get a good pair of tweezers, which are useful for plucking bits of drooled filament out of places they shouldn't be.

www.it-ebooks.info

Figure 6-2. *A painting knife is a good tool to remove a part from a tape-covered platform*

Picking Off Support and Cleaning Up The Print

If your part needed support, you now have to pick it off. This can be a painstaking process, and the precise procedure you use will depend on the tools you have available. Be careful because the plastic can be sharp; protect your eyes from the possibility of small flying sharp bits.

Grasping the support with needle-nosed pliers and twisting it sometimes works well for sparse support; you will need to experiment and see what works for you. As discussed in Chapter 5, it's best to design your model in the first place to avoid big areas of support because they are very hard to remove. Chapter 10 includes an extensive discussion on ways to clean up prints.

Restarting or Shutting Off the Printer

When you take your print off the build platform, you can either turn off the printer or create your next print. If your manufacturer gave you slicing settings, it is likely that there are some shutdown lines of G-code in the standard setting, or the firmware may take care of some activities.

For example, a printer without a heated build platform might add a few lines to every G-code file like those in the following example. The first line turns off the extruder heater (sets the temperature to zero); the second line sends the *x*-axis to its home (zero) position; and the last command disables all motors.

```
M104 S0
G28 X0
M84
```

In general, if a print finished normally, you probably can create or load in another G-code and just run the next job. If you are not planning on using the printer again right away, it is best to turn it off and unplug it.

Manually Controlling Your Printer

From time to time, you may suspect that your printer has a problem, or you may need to manually back out of an awkward failure that left a part skewered on the extruder. In those cases, you will want to use the Print or Control window in one of the host programs to send a G-code single line or two, or use the other manual controls that most host programs provide.

Chapter 11 talks about how to diagnose common problems. However, there are measures you might want to take as part of routine printing. For example, what do you do if you want to change filament colors, but you forgot to pull out the previous filament when you turned off the printer (and now it is melted into the nozzle)?

www.it-ebooks.info

All the procedures that follow use the printer control mode in the host program you are using (or in MatterControl, ADVANCED CONTROLS and then PRINTER CONTROLS). There are variations among the hosting programs, but all of them allow sending a single line of G-code at a time, as well as moving the extruder in any axis, heating the extruder, and heating the platform.

■ **Tip** By default, most printers use degrees Celsius (C) for temperature and millimeters (mm) for length measurements. If you are having trouble thinking in millimeters, it might be helpful to know that there are about 25.4 mm in an inch, 210 degrees C equals 410 Fahrenheit, 115 C is 239 F, and 230 C is 446 F (to pick some commonly encountered temperatures.)

Stopping a Print

Sometimes a print does not stick to the platform and starts to slosh around, or the print you thought would be fine without support isn't going to work after all, or you just look at what is building and scratch your head about how your lovely computer image could have turned out like that. When a problem like this becomes obvious, the best thing to do is to click the "kill job" or "stop" button, as the case may be in your host program.

If the print got jammed under the extruder somehow, you may want to move the extruder away manually (see "Backing Out of a Bad Situation") and then retract the filament. Once you get the failed print off the build platform, turn off the printer if you are not going to try again. Note that G-code to turn off heaters and other shutdown activities will not be executed if the job was killed part way through. Typically it's a good idea to cycle power on the printer just in case the partial print left it in some strange mode. If the failure rammed anything into the extruder, you might want to check that the build platform was not thrown out of alignment. Check your manufacturer's alignment instructions.

Changing Filament

When you finish printing a part, it's a good practice to retract the filament out of the nozzle so that you do not have to do get remaining filament out of the hot end as we will describe shortly. To retract the filament, as soon as the print job finishes, open the printer control panel and type in 10 mm of retraction. You can click the button to extrude 10 mm a few times; the filament should pop out of the input device after an appropriate number.

If you have a Bowden extruder (see Chapter 2), you only really need to get it out of the hot end to have the option of pulling it out easily later. Some printers also add commands to retract after every print job so you do not have to think about it. Even these printers, though, normally do not retract if you kill a job mid-print for some reason.

Suppose you forgot to retract the filament last time. You have bright pink ABS filament in the nozzle and you want to make an object in white in PLA. Do the following:

- Type in the temperature appropriate to the *filament that is in the nozzle* (in this case, ABS, so about 230 degrees; see Chapter 7).
- You will see a button to click to turn on the extruder. Click the button.
- Look at the monitoring display and wait until the temperature is near the right level (but not all the way there, because then you will just melt more filament into the nozzle.)
- Retract 10mm at a time until the filament springs out (or until you can pull it out the rest of the way, for printers that have a release).
- Then change the extruder temperature to the level appropriate *for the new filament* (in this case, PLA, so about 210 degrees.) If there is plastic left in the nozzle, you need to purge it by pushing it out with the new filament. This has to be done at the higher of the two extrusion temperatures (in this case, 230 C). (If there is a big temperature difference between the two filaments, you might have to use an intermediate filament to purge out the old one, or use the "cold pull" technique described in Chapter 11 to clean it out.)

www.it-ebooks.info

- Start the new filament into the extruder in whatever way is appropriate for your printer once the extruder is at the appropriate temperature (look at the temperature status graph.)
- Once it is nearly in, type in 40 mm or so and extrude.
- Keep extruding an additional 10 mm or so at a time until the filament stops coming out the old color. Using a skirt on your next print will take some of that away too, as discussed in Chapter 5.
- You can then run your next print with the new color and material.

■ **Tip** You could, in principle, use the preceding process to change out filament mid-run to have a multi-color or multi-material print with one extruder. Experts can and do try this (by using "pause"). It's very tricky, though, and results may be unpredictable.

Changing Temperatures During a Print

If a print looks like it may be having trouble sticking to a heated platform, you might want to raise the platform temperature just a few degrees. Typing a new temperature under "Heated bed" and clicking the "Set" button should change the settings. You can change your extrusion temperature on the fly this way too (by changing extruder temperature and clicking Set) if you decide you should be running a little hotter or cooler.

Basic Hardware Troubleshooting

Sometimes you'll want to determine whether a printer is having hardware issues of some type, so it's good to be able to try some basic commands to debug what is going on.

Checking Motion of One Axis at a Time

If you want to check the motion of one axis in a controlled fashion to see whether something is broken or loose, the printer control panel in the host programs allows you to move the axis in a positive or negative direction by typing in a positive or negative number (or in some cases by typing a value in to a + or – box.) In Chapter 2 you saw that the *z* axis is the vertical axis; *x* and *y* are in the plane of the build platform.

If nothing happens when you enter a value, you may be at an end stop. Try entering a small value to move in the opposite direction. (For example, if nothing happens when you input +10 mm in *x*, then try –10 mm). Use small values—a few mm—if you are trying to debug a problem. Some machines are also configured with software endstops. It is not uncommon for machines to refuse to move in the negative direction past the point where they were when the machine started up until it has been homed, because it thinks that that position is zero.

If you can't get any axis to run, you may have a connection problem; be sure your USB connector is firmly attached and that your printer hardware settings are correct for your printer.

Backing Out of a Bad Situation

If you forget to take a previous print off the platform, or otherwise do something you are not supposed to do, you may find the extruder jammed into a print or blocked somehow. Because it's hard to figure out which way is +*x* and which way is –*y* under battle conditions, you might want to familiarize yourself now with how your printer is set up in case you need to walk your way out of a problem with the manual controls.

www.it-ebooks.info

Extruder Not Extruding

If the extruder is moving around but no material is coming out, there are a few possible problems. The extruder nozzle might be jammed, or the extruder motor might not be pushing out filament. To debug this problem, you may have to trick the printer a little to get the information you need.

Most printers are set up so that the drive system does not try to push filament through a cold extruder. However, for printers with a visible filament drive gear, it's helpful to see whether the gears are turning even though nothing is coming out. A drive gear and its relationship to filament are shown in Figure 6-3.

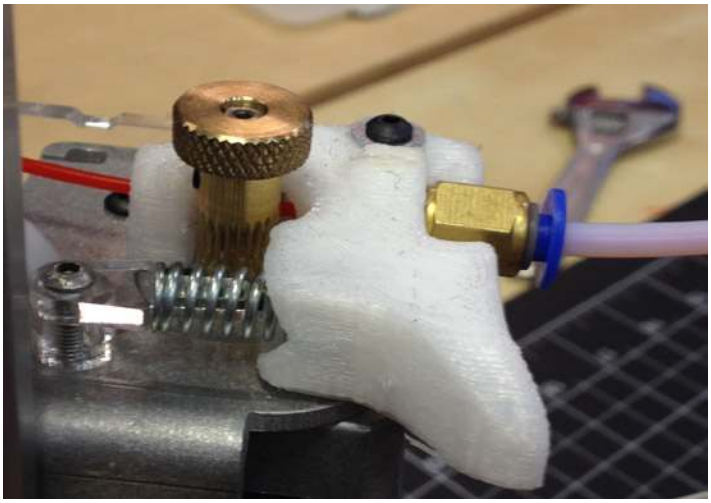


Figure 6-3. *A visible (Bowden extruder) filament drive gear*

You may not be able to see anything if filament is stuck in the nozzle. But if no filament is in the extruder drive, you can send the following line of G-code to the printer to tell it to override the need to heat up the extruder:

```
M302
```

And then tell the gear to extrude a few tens of mm of filament. See if the gears are turning. If not, you have some other failure.

If the gears do turn, then your nozzle is probably clogged. To unclog a nozzle, follow your manufacturer's instructions. If your manufacturer did not provide any suggestions, you can try the following.

- Heat the extruder a little above what you used for your last print and try manually extruding as we did for the filament-changing process earlier this chapter. If you have input an `M302` command, be careful not to try to extrude any filament until the head is at the appropriate temperature.
- If nothing comes out, manually retract the filament. Take a look at the end of it—is there anything burned or strange on it?
- If not, try breaking off the end cleanly and extruding again.
- If all that fails, and your printer is able to accept nylon filament, try the "cold pull" procedure described in Chapter 11.
- You might also try searching online using the phrase "Unclog extruder <*your printer name here*>."

www.it-ebooks.info

Running from an SD Card

A microSD card is a tiny removable storage device, commonly used in digital cameras. Some printer firmware allows the printer to run G-code from a microSD or regular SD card. In either case, if you have a small screen on your printer, it probably will allow you to choose a file to run from an SD card.

For printers running Marlin firmware, if a G-code file named `auto0.g` is present on the SD card, the firmware will recognize it as a G-code you want to print and will automatically start running the code. This is convenient if you have a relatively mature G-code you want to run repeatedly (for demonstrations, for example) and you do not have a screen on the printer.

However, if you are running from an SD card, you may find yourself trotting back and forth to your computer a lot if you need to adjust the model or settings more than once. There is also no way to know how many layers are left to go, and no feedback about the temperature of the extruder and heated platform unless your printer displays that information on a small screen and/or allows you to have a USB cable plugged in while running from an SD card.

To kill a job running from an SD card, press your printer's reset button and then remove the SD card so that it will not auto-start again. Power off the printer if you are not going to try again, because G-code commands to turn off heaters and other shutdown activities will not be executed.

■ **Caution** If you have a printer that can use an SD card, be sure to remove it when you do use a USB connector to drive the printer from your computer. Otherwise, commands from a file on the SD card (such as `auto0.g` on a printer running Marlin firmware) and whatever G-code you are sending from your computer will interleave, and nothing good will come of that.

Micro-SD adapters that allow a computer to write on a microSD card from a USB port are available from places that sell office electronics or cameras. Do not remove the SD card while the printer is running; G-code is read and executed one line at a time. You will stop the print and have no way to recover.

■ **Tip** If you have a printer that can use an SD card but can only see a file called `auto0.g`, always copy each file you want to print onto the SD card twice. So if you had `RabbitEars.gcode` that you just made on your computer, copy it over twice, remove the existing `auto0.g`, and rename one of the `RabbitEars.gcode` files `auto0.g`. That way you always have files that you have tested ready to go, as long as you have a computer available to manipulate the files on the SD card. If you do a lot of demonstrations, it can be a very convenient way to have several standard printable models handy. Only the `auto0.g` file will start automatically, but the printer can still see the other files and can print them if instructed to do so.

Summary

In this chapter you learned how to load the model you generated in Chapter 4 and sliced in Chapter 5 onto the printer. This sliced file is a G-code file, and we covered what is in a G-code file and how to manipulate one if needed. We also reviewed how to control the printer manually and how to debug some common problems. In Chapter 7 you will learn about types of materials, and then Chapter 8 will tie up this part of the book with case studies of different types of objects.

www.it-ebooks.info

CHAPTER 7

Material Considerations

This book focuses on 3D printers that feed filament into an extruder, which melts the filament and lays it down a layer at a time. *Filament* is a thick thread made of a variety of materials such as plastics, nylon, and elastomers, typically in one-kilogram (plastic) or one-pound (nylon) spools. Figure 7-1 shows a one-pound nylon spool and a one-kilogram spool of polylactic acid (PLA) plastic.

Figure 7-1. *Typical spools of nylon (top) and PLA (bottom) filament*

This chapter covers the materials that a consumer filament-using printer can use, with a focus on non-proprietary filament. (Some printers use proprietary cartridges for their filament to manage some of the issues discussed in this chapter. These cartridges are typically far more expensive, however, than generic spooled filament.) This chapter covers the types of materials available now, which applications are particularly suited for which materials, and things to think about when printing in one material versus the other.

www.it-ebooks.info

An open source community effort is underway to develop a sticker for filament spools that would encode some of the printer settings. A system called the Uniform Filament Identification system (UFID) is under discussion in the user community to create a standard for these stickers.If this effort is successful (and if manufacturers accurately provide the information), a user may not need to be concerned about adjusting printer settings based on the material used because this information may be picked up by printers automatically. Until filament manufacturers implement such standards, though, users need to deduce and input various settings describing the filament diameter and the appropriate extruder and build platform temperatures.

Some filaments require a slower print speed than normal or special cooling settings to ensure that one layer cools before the next one is laid down. The settings suggestions in this chapter are typical; you may need to make adjustments based on experience with a particular filament/printer combination.

■ **Caution** Build a small test object to try out settings for a new brand of filament before embarking on a many-hour big print.

Filament Quality Control

3D printers initially used filament that had been intended for welding plastic tanks. The filament diameter did not need to be very precise for that application, and so in the early days of filament-based 3D printers, the quality control on filament diameter was often inadequate. As the 3D printer filament market has grown, quality control is improving, but there are still occasional inconsistencies.

Common filament diameters are 3 mm and 1.75 mm. However, these are nominal diameters, and the actual diameter may vary. Many experts own a pair of calipers to measure the actual diameter for each manufacturer and check the filament diameter first if the printer seems to be laying down too much plastic or not extruding at all. If the diameter is bigger than the extruder is designed for, the printer may jam or stop extruding. To check the diameter of filament, use a pair of calipers, as shown in Figure 7-2. In fact, it is a good idea generally to have a pair of calipers available to check print results and compare prints to actual desired values.

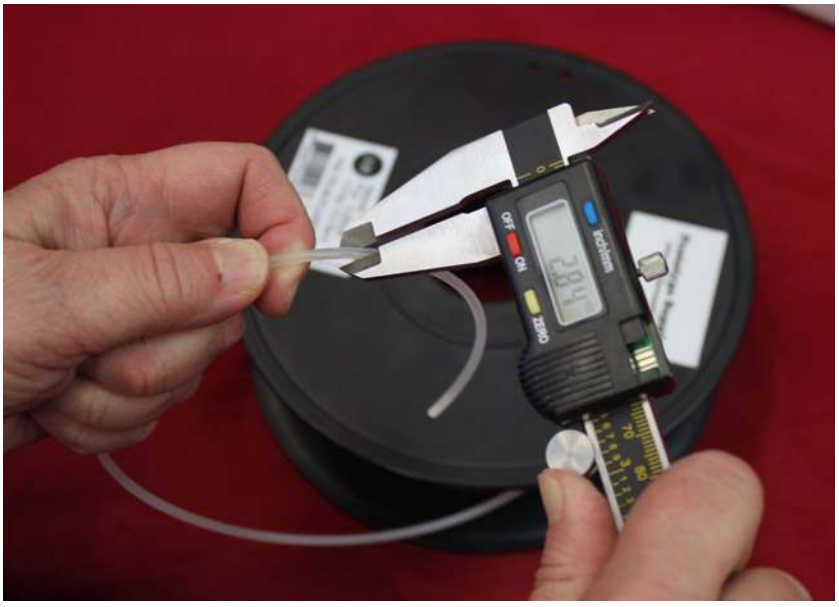


Figure 7-2. *Checking filament diameter with a pair of calipers*

www.it-ebooks.info

If the diameter is too small, the print quality may be degraded. Commonly "3mm" filament may actually measure around 2.87 mm or so. It is a bigger problem for filament to be too big than too small, so manufacturers aim for a nominal diameter in the 2.85 to 2.9 mm range, with 3 mm being an absolute maximum.

■ **Tip** After you check the actual diameter of your filament, adjust the "filament diameter" or equivalent setting in your slicing program accordingly. You may want to save one slicing-software setting per manufacturer. Sometimes different color filament from the same manufacturer or different batches from the same manufacturer can vary.

Poor quality filament may have air bubbles, which will result in erratic print quality. Worse, contaminant particles can block the extruder nozzle. If a printer suddenly starts having problems extruding, an erratic filament diameter or filament contaminants should be early suspects. Be sure to use 3D printer filament, and not something that looks like it but was not intended for the purpose.

Can you start with raw plastic and make (or recycle) your own filament? Unfortunately, this is not as easy as it seems, largely because of the need for precision already noted. There is also always a risk that a raw plastic may have unexpected additives.

There have been some entrepreneurial efforts to create desktop machines that make filament from raw material, but they are still at a pretty early stage. Track developments on crowdfunding sites like Kickstarter (www.kickstarter.com) if you want to pick up an experimental machine when they stabilize enough for your taste.

Selecting and Using a Filament

Selecting material for a project requires trading off many different factors based on the use of the object, available materials, and cost. Some 3D printers are only able to print in one material and then the issue becomes whether it is possible to use that material for the intended purpose.

If your printer gives you some options, however, there are some significant differences in material properties among the common materials used by consumer-grade printers. Most 3D printing materials are classed as *thermoplastics* (polymers that soften as they melt and then harden again when cooled) or *thermoplastic elastomers* (TPEs), which are a combination of a plastic and a rubber.

Common 3D printing thermoplastics include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and nylon. Depending on the characteristics of the extruder, printers may also be able to handle polyethylene terephthalate (PET) and polycarbonate.

There are also more exotic materials and mixtures for interesting esthetic effects. More types of filament are coming up all the time. This chapter does not presume to be an exhaustive list, but rather an attempt to sample some typical and up-and-coming options.

Looking at the manufacturer's specifications for any given filament is a good idea. Numbers given in this chapter are typical numbers. Some extruder nozzles, however, may have an upper temperature limit below that needed for some of the materials mentioned here.

■ **Caution** Open source slicing software does not check to see whether a user is exceeding the upper limits of any given printer model. Printer firmware may or may not catch attempts to exceed limits. Be sure to check the manufacturer's specifications before setting up for any particular extruder and bed temperature.

The following sections lay out some of the key considerations when choosing a material to make your object and when printing in that material. First you will need to think about whether the material is strong enough at all, and how to orient the print to take advantage of the fact that a 3D-printed part will be stronger along a layer than across layer boundaries. Next, we will talk about issues that arise when printing in different materials—whether a heated bed is required, whether drafts are a problem, and whether you might need to print more slowly with some materials.

www.it-ebooks.info

Directional Strength

How strong is something made on a 3D printer? The answer depends on the filament material, but also on the details of the print. Prints are weakest in the *z* direction (because the layers can pull apart), so the orientation of a print on the print bed also has implications for strength of the printed object. Design of an object should take into account the following:

- The inherent strength of the material
- Whether the object's operating environment will get hot
- Whether the object's operating environment will contain any chemicals that affect the material
- The direction in which the object will need to be strongest
- Support structure needed in various build orientations
- Thickness of the outer shell of the model
- Infill pattern and density
- Any connections with other (non-3D-printed) parts
- Brittleness— the ease with which a part (particularly a small part, or support) will break off
- Tolerances and clearances

It is tempting to create a 3 mm hole in a part and print a peg that is exactly 3mm in diameter to fit in that hole if you are looking at an idealized computer model of your peg and your hole. This will not work in the real world, though (as opposed to computer-screen world) because small clearances are needed for one part to actually go through another. For a consumer-level printer, a clearance of half a millimeter or so is probably about the smallest practical space required between parts.

As discussed in Chapter 5, many settings in slicing software specify the external and internal structure of a part. Chapter 8 discusses some typical case studies to make it more concrete how these factors interact.

The Right Print Bed

Prints need to stick solidly to the build platform so that they do not shift or fall off while the piece is printing. On the other hand, the platform or the print may be damaged if the print is stuck down too firmly.

For many materials (like ABS and polycarbonate), the platform has to be kept warm so that the print sticks to it. Some 3D printers have heated platforms; ones that do not probably cannot print in these materials. Materials that need a heated bed will warp while printing if the bed is not adequately heated. As the lower layers cool, they will shrink and pull up from the bed at the corners. The hot layers on top will be a bit bigger, and as they cool the part will warp more and more as the upper layers also contract.

Beyond heating, the surface of the platform needs to be a material that is compatible with the print material. At the moment figuring out what sticks to what is fairly empirical. Blue painter's tape (3M seems to work best) and high-temperature Kapton tape (transparent gold-colored tape) are common printer bed materials. Glass, often with glue or some other adhesive coating, is becoming a more popular printing surface. Follow your manufacturer's directions, but generally the following rules of thumb hold:

- PLA will stick well to blue painter's tape. Typically, we think of this tape as something that pulls off a wall easily, but interestingly the 3M tape in particular seems to be just the right surface for PLA to stick to sturdily. Blue tape is available in wide rolls that can cover a smaller print bed in one shot, which avoids tape edge lines in the first layer of the print.

www.it-ebooks.info

- PLA does not need a heated bed if the print bed is covered with blue tape. However, if the bed is covered with something else (for example, Kapton tape), the bed needs to be heated to a low temperature to make the model stick.
- If you have a heated bed covered with Kapton tape and you decide to try blue tape on top to print PLA with the bed cold, be sure the bed is cold and put on the blue tape at right angles to the Kapton so that it does not tear off the Kapton when you remove it. Blue tape also tends not to stick to Kapton tape as well as it does to bare glass, and the PLA parts warp enough to pull up the tape.
- Nylon does not like to stick to many materials. Garolite (sometimes called phenolic or Bakelite) is a good material for print beds used for nylon. Some printer manufacturers sell a Garolite platform that can be switched out instead of (or on top of) a heated platform.
- Other materials (like ABS) do well on a heated bed covered in high-temperature tape (like Kapton tape). Some printers come with glue sticks or other materials to enhance printed part adhesion. Experiment a bit to see what works for your printer and the parts you are printing.

Ventilation and Drafts

There are few standards for materials for 3D printing just yet, so it's generally a good idea to ventilate the area around your 3D printer. Some materials (like ABS) smell fairly strongly, so think about who and what else is nearby when using the printer.

However, direct airflow on a printer when it is printing can be either a positive or negative thing (PLA often does better when cooled with a small fan, but ABS needs to be kept warm). It is usually best to ventilate by pulling air away from a printer rather than blowing air onto it. Generally airflow onto a print should be carefully directed and controlled with a fan, and you should avoid printing in the presence of erratic or unpredictable drafts.

Figure 7-3 shows a PLA fan on a printer cooling a print. The PLA fan is the small round object held on with two cable ties.

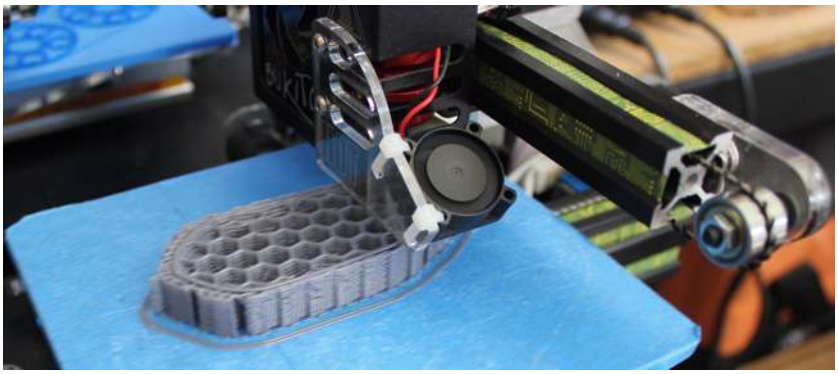


Figure 7-3. *A PLA fan cooling an object*

www.it-ebooks.info

Storing and Handling Filament

Most filament is *hygroscopic* (absorbs water from the air), which can affect its properties and the quality of a print. Keep spools of filament dry and avoid extreme temperatures. If you buy a spool of filament and are not going to use it for a while, keep it in the original sealed package until you are ready to use it under environmentally stable conditions. It's probably unwise to store it in a damp garage that gets very hot in summer, for example.

■ **Tip** Before you begin a print, be sure filament loops do not cross over or under each other on the roll. Try to loosen the filament a little so it is not overly tight, particularly if you are starting a print near the end of a roll. If the filament knots in place even briefly, it can pull on the extruder and affect print quality (or stop the print). A plastic lazy susan (from a kitchen supply store) works well if it is the right diameter to carry the filament roll. See Figure 7-4 for the wrong way!

Figure 7-4. *The wrong way to lay out filament at the start of the print (crossing a loop under another)*

Temperature and Speed Settings

When you print in a particular material, there are three major settings to worry about: temperature of the extruder (otherwise known as "print temperature"), temperature of the heated bed (or absence of a heated bed), and the speed of printing. Table 7-1 lists some typical values for materials that are discussed later in this chapter. Chapter 5 covers printer settings in more detail along with the effects of the geometry of the object being printed, but this table will give you a sense of the relative difficulty of printing with some of these materials. These are only examples, though, and different formulations and printers may perform best with significantly different settings.

www.it-ebooks.info

Table 7-1. *Filament Characteristics*

Material	Print temperature (deg. C)	Bed temperature (deg. C)	Speed
PLA	210	60	Normal
		Unheated/blue tape	Normal
ABS	240	115	Normal
Nylon 618	240	Unheated/Garolite	Normal
HIPS	240	115	Normal
Elastomer	210–225	Unheated/blue tape, bare glass	Very slow
PET	Nominally 212–224; some users suggest 250	80	Slow
Polycarbonate	> 270	Very high	Varies

Will My Filament Spool Run Out During My Print?

Filament is fairly expensive, so you want to use every bit on the spool if you can. However, you also do not want to run out during a print. Slic3r and Cura (described in Chapter 5) both give an estimate of the length of filament that will be used in the print. When you get near the end of a roll, pull some out, measure it, and note roughly what fraction of the remaining filament remains after subtracting that part. That will let you estimate whether your print will work or not.

For example, if you pull out a meter and it's about a quarter of what is left on the spool, you have four meters of filament left. If your print says it will take 3,900 mm (3.9 meters), you might not want to risk it.

Filament Materials

The following sections describe a few of the common materials in a bit more depth. PLA, ABS, and nylon are currently the most frequently encountered filaments, but we will talk about a few of the more exotic ones, too.

Polylactic Acid (PLA)

PLA is one of the more common materials for 3D printing. It is typically made from corn or similar renewable materials and is biodegradable. It can be extruded at a relatively low temperature (around 210 C) which means it is less challenging to make an extruder print PLA versus other materials. Printing PLA does not require a heated bed. The downside is that it becomes soft at hot-car-dashboard temperatures, so a little thought needs to go into when it is and is not a good idea to print something in PLA.

That said, PLA is a very versatile material that is generally fairly forgiving to print. Many printers have a small fan to cool PLA as it prints to improve print quality. It can be difficult to get support off cleanly with PLA prints (see the discussion in Chapter 5) because the material is still fairly ductile when cold and so does not snap off cleanly. Slicing algorithms in this regard are steadily improving, though.

PLA comes in many colors and opacities, and even in a version that changes color from white to bright purple when exposed to UV light (like sunlight).

PLA also works well in the ancient *lost wax* technique for making metal and glass objects, which is discussed at length in Chapter 9.

www.it-ebooks.info

■ **Caution** Because PLA becomes soft at a relatively low temperature, it is unwise to use PLA for any application where the printed part might get warm. For example, it's not a great idea to print critical parts of a RepRap printer (described at length throughout Chapters 1 and 2) in PLA and then put the printer in an un-air-conditioned room during a heat wave. (Yes, it has happened; the result was referred to afterwards as the "Dali printer" for its innovative geometry.)

There are some exotic proprietary material blends that will print with settings like those for PLA. These are thermoplastics infused with other materials to give interesting printed material properties. Laywoo-3d is a thermoplastic infused with finely ground wood. Varying the temperature a little during printing will give the print a wood-grained appearance. Thin-walled prints in Laywoo-3d can be a little fragile.

Similarly, Laybrick is a thermoplastic infused with milled chalk to look like stone when printed.

Acrylonitrile Butadiene Styrene (ABS)

ABS is another common consumer printer filament material. You may know it best as the plastic used to make many toys (including Lego pieces). It is a hard and durable plastic and stays strong at higher temperatures than PLA does. However, it does tend to warp when cooling and is challenging to print without a heated bed.

ABS is also a good choice for parts that need a lot of support because support typically will snap off more cleanly in ABS than in other common materials.

Nylon

Nylon is a versatile material because thin nylon structures are flexible but thicker ones are fairly stiff and strong. Nylon is often a good choice for functional parts, but you need to be careful to think through the directions of the layers and where the part is weakest. Nylon 618 and nylon 645 are two available formulations (the numbers refer to the molecular structure of the particular formulation).

With nylon, it is particularly important to be certain that you are getting 3D printer filament. Other products out there (like weed-whacker filament) may appear similar but may contain nozzle-clogging impurities or materials that give off toxic volatiles when heated. Nylon filament is particularly prone to absorbing moisture from the air. Keep nylon filament dry. When you start to print nylon, small puffs of steam come from the extruder that can be startling if you do not expect it.

Nylon typically comes in white filament, but pieces printed in nylon can be dyed with dye appropriate for nylon fabrics. Designer Michael Schmidt and architect Francis Bitonti created an articulated 3D printed dress in nylon for entertainer Dita von Teese in one of the more extreme examples of 3D printing in the fashion industry. Although this was not printed on a consumer printer (it consumed a large amount of printing capacity at the Shapeways service bureau when it was created), it shows what is possible. You can see the dress, dyed black, lacquered and with thousands of added Swarovski crystals, at Michael Schmidt's website (www.michaelschmidtstudios.com.) The dress was made with a powder-based printer, but you can imagine the possibilities for 3D-printed nylon fashions.

Nylon requires a high-temperature nozzle and special unheated platform surface (for example, Garolite) and so may be beyond the capability of your printer.

■ **Caution** Be sure the filament you buy is intended for use in 3D printers. Do not go on appearances alone. The chemistry and material composition of the filament is important both for print quality and your safety during printing (review the safety and ventilation section in Chapter 2).

www.it-ebooks.info

T-glase (PET)

PET is a clear plastic that is commonly used in water bottles. It is sold in 3D printer form under the brand name t-glase. It is a plastic that is approved by the U.S. Food and Drug Administration for direct contact with food. As of this writing, Taulman (the makers of t-glase) has said on its website that the company was awaiting direction on the rules for declaring a part printed with t-glase to be food-safe.

Additionally, PET is a very transparent material. A 3D-printed part will not be perfectly clear in all directions because of the layer lines, but will be translucent, particularly in thin-walled objects. It has a relatively low melting point and thus should not be used for parts that will be in hot environments.

Polycarbonate

Polycarbonate is a very strong material but is still somewhat experimental for consumer 3D printing use. It can be challenging to print because it is difficult to get to stick to the build platform. But if you are at the more industrial end of the printing spectrum, polycarbonate is a developmental material to watch for the future. Be sure to read the filament manufacturer's documentation and consider your printer's limitations carefully.

Thermoplastic Elastomers (TPEs)

Elastomers are combinations of a thermoplastic and a rubber. Prints made with a TPE (such as NinjaFlex) are strong and flexible. However, the print has to be created very slowly to avoid overstretching the filament during printing. This is more challenging with 1.75 mm filament than 3 mm because the thinner filament tends to flex and be difficult to manage. Bowden extruders can exacerbate this problem because the filament may flex too much between the drive gear and the nozzle.

Once these challenges are overcome, however, the unique qualities of TPEs will probably enable a lot of new applications of 3D printing. Thin TPE prints can be crumpled in your hand like a thin rubber mat, and thicker-walled prints are like shoe soles—tough yet flexible.

Research Filaments

Researchers are using consumer-level 3D printers to fabricate many different exotic materials. A group at the University of Warwick in England and their collaborators created a material they dubbed "carbomorph" out of a mix of polycaprolactone and a carbon black filler to make a mildly electrically conductive filament. They used the filament to print simple piezoresistive sensors that could detect flexing of a surface.

These conductive filaments can be embedded in other printed objects (by using a printer with two or more heads, as described later in this chapter) or attached to other surfaces. The details of the work can be found in the open access journal *PLOS ONE* (www.plosone.org.)

■ **Tip** The *PLOS ONE* open-access journal (*PLOS* stands for Public Library of Science) is generally a good source for freely available peer-reviewed reporting on uses of 3D printing. The full citation of the conductive filament work is: Leigh SJ, Bradley RJ, Purssell CP, Billson DR, Hutchins DA, "A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors," *PLOS ONE* (November 21,2012); 7(11): e49365. doi:10.1371/journal.pone.0049365. (www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0049365)

---

www.it-ebooks.info

Multiple Extruders

The choice of materials gets more complicated with printers that have more than one extruder and that can thus print in more than one color or more than one material at a time. If you are using, say, two colors of PLA, probably there will not be any problems other than creating the two-color model in the first place. See the dual extruders case study in Chapter 8 for examples of the process for developing two-color or two-material models.

Printing Dissolvable Support

Filament-based printers need to support objects that have overhangs. One way to make the process of removing filament less difficult both on you and on the object you have printed is to use dissolvable support.

As the name implies, *dissolvable support* involves printing support in a different material than the primary object, preferably one that has different chemical properties than the primary object's material. HIPS (high-impact polystyrene) is one common support material; it dissolves in the solvent d-Limonene. HIPS will print adequately with the same settings as ABS, so one good way to print something that needs a lot of hard-to-get-at support is to print the part on a dual-extruder machine with one extruder printing the main part in ABS and the other printing support in HIPS. Then the support can be dissolved away.

If HIPS is not available, just printing support in a different color of the same material used in the primary part can make small bits of support easier to identify and remove, although as already noted this can also make any mistakes more visible.

■ **Tip** In general, it is easier to remove support from an all-ABS print than an all-PLA print.

Dual-Extruder Printing with Two Different Materials

Printing in two different materials at the same time can be tricky because you may be printing materials in close proximity that individually would be printed with different platform and extruder temperatures, which may mean that one or the other will not be optimal. Here are some considerations to bear in mind if you embark on a two-material print:

- Which material will (primarily) be present in the first few layers? The bed temperature or platform surface material should generally be set to favor the material that primarily will directly interface with the platform. A raft of one material or the other can solve this problem.
- Are the materials extruded at very different temperatures? If so, you might have to experiment with printer speed to give layers more time to cool before another layer is placed on top.
- Some experts feel that it works better to have each extruder set for a slightly (5 to 10 degrees C) lower temperature than would otherwise be nominal with a single extruder printing that material. The two heads put a lot of heat into the piece, and adjusting temperature downward seems to result in better prints. Others feel that this is a bad idea because inter-layer adhesion can be compromised by giving you a lower bonding temperature in a print that already has more layer cooling time than normal. There are exotic ways to manage this, but at the expense of very time-consuming prints.
- Consider whether the part will be stressed in any particular direction and be cautious about where you place material-to-material interfaces that might be weak spots.
- Think about where the "bottom" of the object should go to minimize support.

www.it-ebooks.info

- You will need to pick one of the materials to be support (if you are not having one material used exclusively for support). Think about which material will be the easiest to snap off if you use it for support.
- Are the materials likely to stick well to each other? If not, the design of the object may need to take account of that—by having one material run through the other, for example, as shown in Figure 7-5. This piece was made from ABS and nylon. The nylon is embedded in each block of ABS, and only ABS touches the platform, minimizing the opportunities for the two materials to pull away from each other.

Figure 7-5. *A two-material print (ABS squares and nylon connectors). Dual-material bracelet design by Diego Porqueras*

- Controlling *ooze* (the nozzle "drooling" a bit when it is hot and filament is left in it) can be a problem in dual-extruder printers.

■ **Tip** A little experimentation with a small test project is probably the best way to test out settings for printing in two dissimilar materials. Dual-extruder prints can take a while to print because the printer has to switch extruders each layer, so it is best to find problems before embarking on a major print.

Summary

In this chapter you learned about the different types of filament, their material properties, and how best to use them in your designs. In Chapter 8 we move on to case studies of several objects so that you can see in context how to think about the best choice of material for a given job.

www.it-ebooks.info

CHAPTER 8

Case Studies

Chapters 4 through 7 covered a lot of information about how to create a 3D model, slice it, and print it in your chosen material. But it *was* a lot of information, so now we will walk through a few different case studies to show you how to think about particular design problems, how to make an object as simple to print as possible, and how to anticipate issues you may have to deal with during the print. The material in this chapter to a degree duplicates the material in Chapters 4 through 7. We don't explicitly refer back to those chapters by and large, but we apply that material here and in some cases expand upon it a bit for a particular case. The goal of this chapter is to give you some intuition about good practices so that you can over time learn all the details without being overwhelmed.

This chapter gives you some typical settings to use and lays out what we think about when confronted with a particular printing scenario. In general, the best strategy is to keep the model as simple as possible and to try out different slicing settings or orientations one at a time. A good open source 3D printer gives you a lot of flexibility, but it also can have a long learning curve. Find some ways of keeping track of what does and doesn't work and keep your settings files stored in some systematic way so that you can reproduce success.

Listings of all the settings needed to run several of the prints on a Deezmaker Bukito open source printer are included in Appendix A. This chapter uses screenshots from the open source host program MatterControl (`www.mattercontrol.com`) and settings appropriate for a Bukito using PLA. As with all open source software, the program's details and precise instructions can and probably will change, and the detailed settings for your printer may vary. All screenshots in this chapter (except for the one from OpenSCAD) are from a beta Mac version of MatterControl, kindly supplied and provided here courtesy of MatterHackers, Inc. and used with their permission.

At the end of this chapter is a section on setting up prints for multiple extruders. This discussion is somewhat machine-dependent, but a quick example of a two-color object built in OpenSCAD will give you an idea of the workflow to get you started if you have a dual extruder machine.

Simple Print

For your first attempt at 3D printing, try printing a simple object. That's easy to say, but how do you know that an object *is* "simple"? To get started, imagine how the object might print up from the build platform:

- Does the object have a big flat area that can be its base on the platform?
- If you put the object down on that flat area, can you print it without encountering any steep overhangs?
- Are all parts of your object substantial, or are there some thin walls?
- Does it have a smooth surface, or is there a lot of fine detail (for example, features like holes or little protrusions less than 2 to 3 mm)? If there is a lot of detail, then this model is *not* simple; see the section "Printing a Complex Object with Fine Detail" later in this chapter.

www.it-ebooks.info

A "yes" answer to the first two questions means that the object does not need support. Even if a surface is very smooth and rises gradually (like a sphere) if it has a tiny contact area with the platform, it will need support that typically will be hard to get off. A "yes" to the third question means that you do not need to be concerned with the special issues that arise when you are printing a vase or other hollow object. And finally, sometimes an object's detail is just too fine to reproduce with a consumer-level 3D printer, although thinking about the orientation of the layers versus the detail can squeeze out a bit more performance.

■ **Note** An object that *appears* simple (like a big sphere) isn't necessarily a simple object to print. Conversely, something that looks very complex might actually not be all that bad to print if you can find a way to avoid the preceding list of issues.

Simple Print Example 1: Heart Pendant

Chapter 4's discussion of options for getting started quickly with 3D printing talked about a small heart pendant (Figure 4-2). This pendant was designed to have a significant flat base, relative to the rest of the structure. There are some minor overhangs, but they are gradual enough that they can be printed without support. It can be printed with standard infill and has a relatively smooth, simple surface with crisp corners and no fine detail. Thus, it is a very simple object to print. Let's try running it through MatterControl.

As you saw in Chapters 5 and 6, most host programs orchestrate slicing your file and loading it onto a printer. To use MatterControl, select a printer and then load in an STL file by adding it to the print queue with the big + symbol or by using the File menu at the top left. Click Advanced Controls to get into the slicing settings area. The program will automatically slice using the slicing program you choose (as of this writing, Slic3r, Cura, or MatterSlice) when you ask it to do something that needs the sliced file, such as exporting G-code.

Figure 8-1 shows the main MatterControl page once you have selected the Advanced Controls and pulled the program open to a full-screen view. In Figure 8-1, there are three files loaded in already and we have launched the advanced controls (on the right). If you mouse over the items in the queue, you will see several options: View, Copy, Export, and Remove. In Figure 8-1, these are visible for the top item in the queue. If you click View, you will be able to view the model in several ways in 3D (you will see that in a minute in some subsequent figures). Copy and Remove do what you would expect. As of this writing, exporting the file is done with the Queue Options tab at the bottom of the page, which allows exporting as STL or G-code files.

www.it-ebooks.info

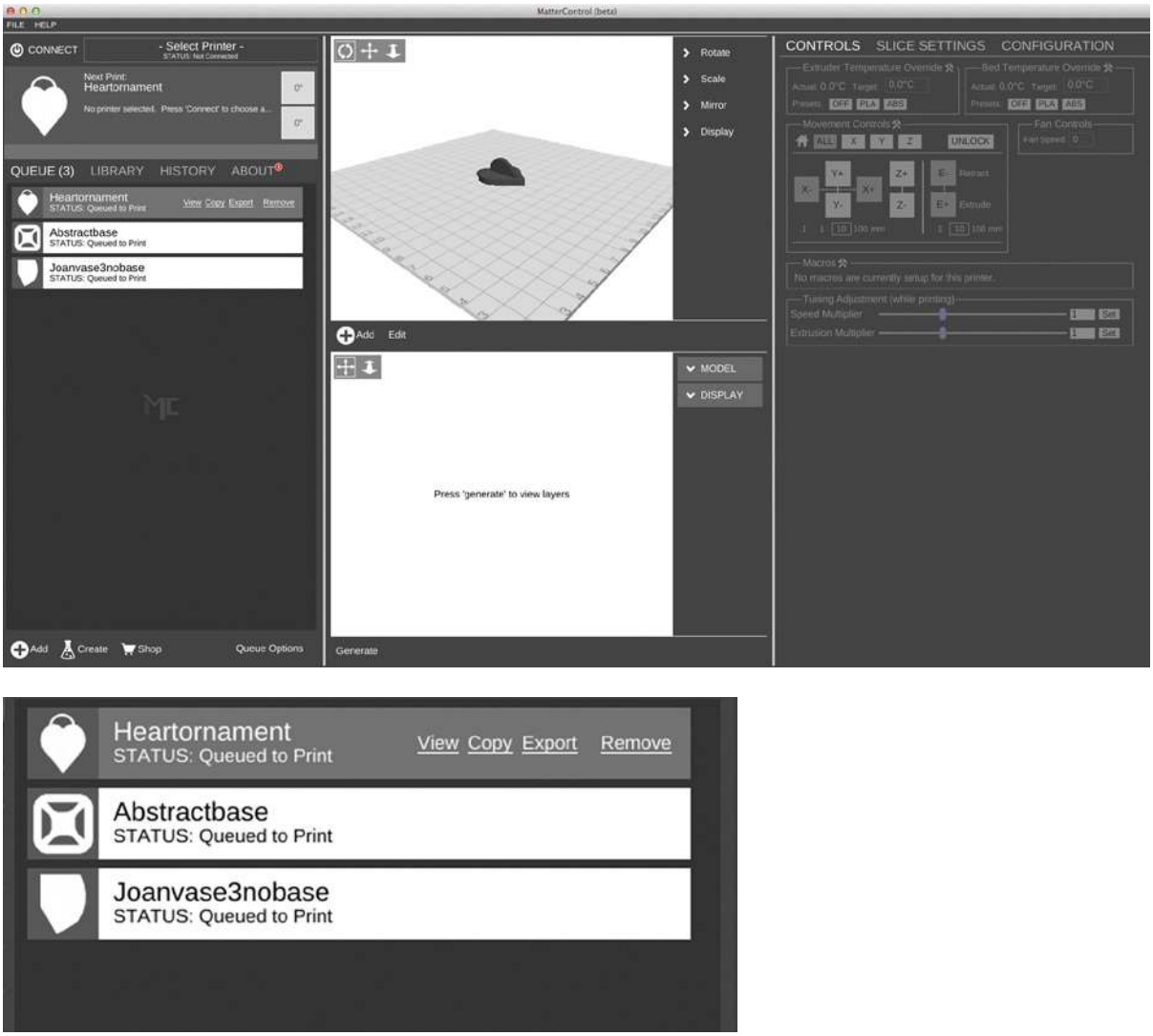


Figure 8-1. *MatterControl screen (dragged out to show all windows—on a smaller screen only some windows will appear by default) and a close-up of the mouse-over menu for the "Heartornament" item*

There are many different slicing settings, as you saw in Chapter 5. Figures 8-2 through 8-6 show some typical settings that MatterControl will pass along to Slic3r. Settings for the other slicing programs are similar. The next few figures show the settings that a user would commonly set; the rest would normally stay the same for virtually all prints and are related to the printer hardware you have, or they are settings that might need to change in some particular advanced circumstances. A full list of the settings for this print is provided in Appendix A.

www.it-ebooks.info

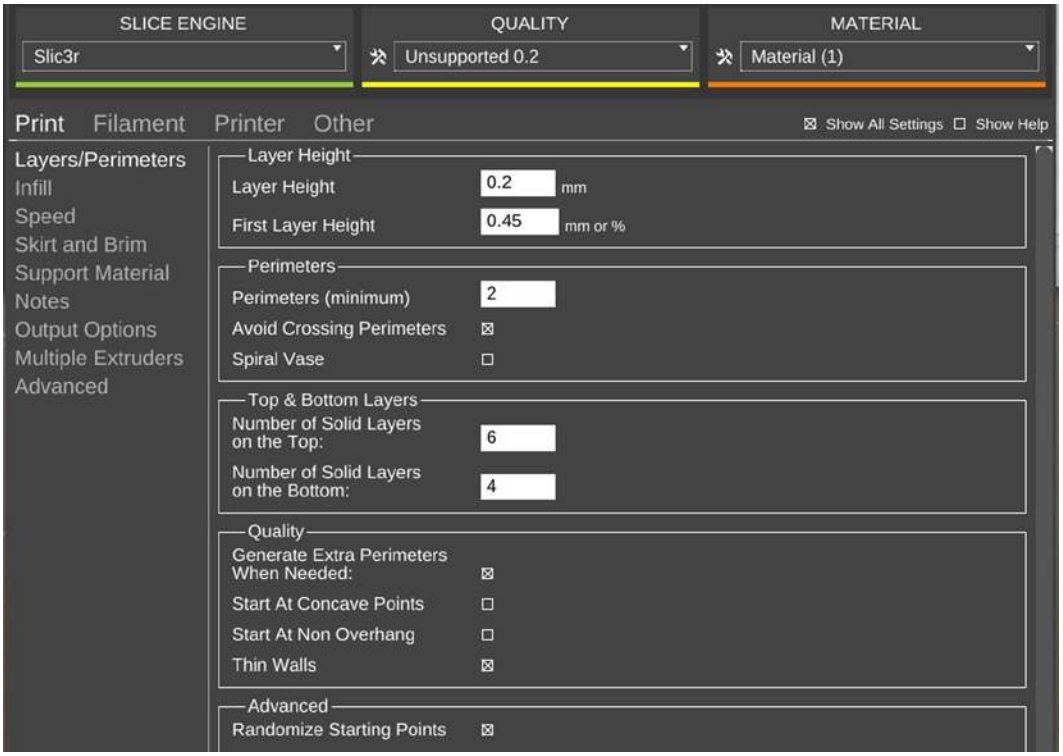


Figure 8-2. *Settings for layers and perimeters for the heart pendant*

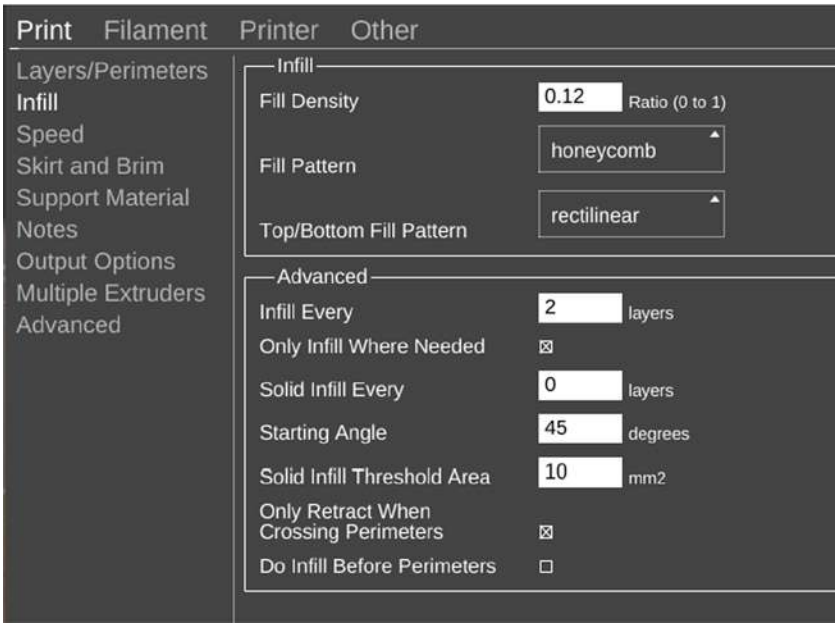


Figure 8-3. *Infill settings for the heart pendant*

www.it-ebooks.info

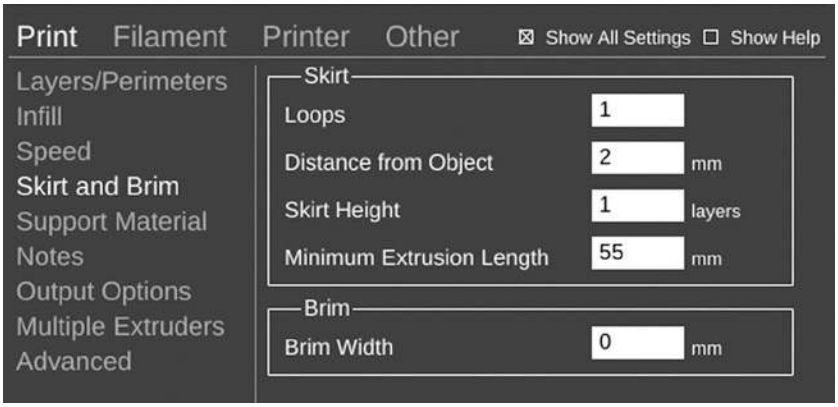


Figure 8-4. *Skirt and Brim settings for the heart pendant (see Appendix A for typical Speed settings)*

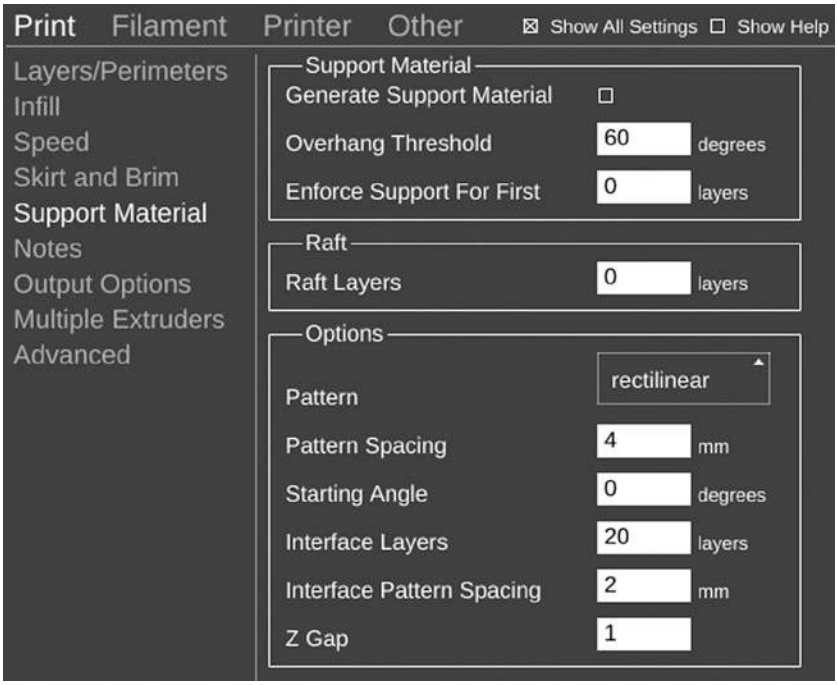


Figure 8-5. *Support Material settings for the heart pendant. These will be ignored, because we did not check Generate Support Material for this case that does not need support*

www.it-ebooks.info

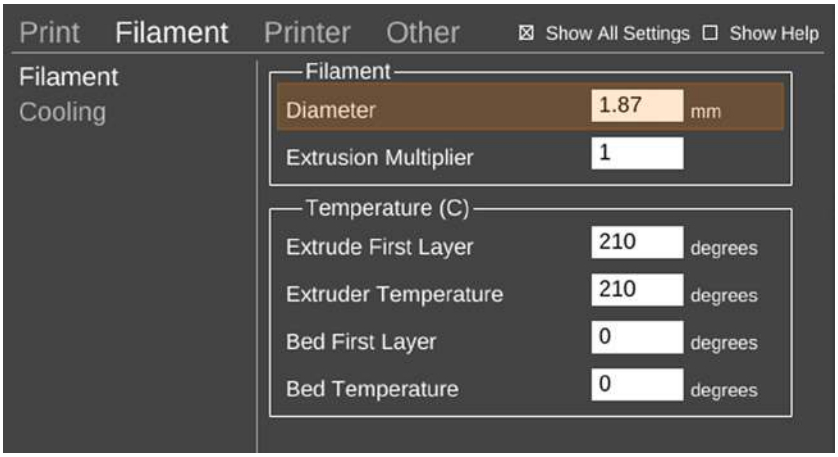


Figure 8-6. *Filament settings for the heart pendant, using PLA on a printer that is using blue tape on an unheated (0 degrees) bed (see Chapter 7's section on printing with PLA)*

The Speed, Output Options, Multiple Extruders, and Advanced settings would not normally be altered by a user, so we skipped screen shots of those sections. See Appendix A for typical values of all settings.

Part of the process of setting up a print is to lay the print out on a print bed. Figure 8-7 shows the MatterControl 3D viewer. The gridwork is the platform (Printer settings tell the program how big this is), and the shaded box is the overall build area. As you can see, the program predicts that the heart will not take up much of the space. Figure 8-8 shows the print starting on the printer in real life for comparison.

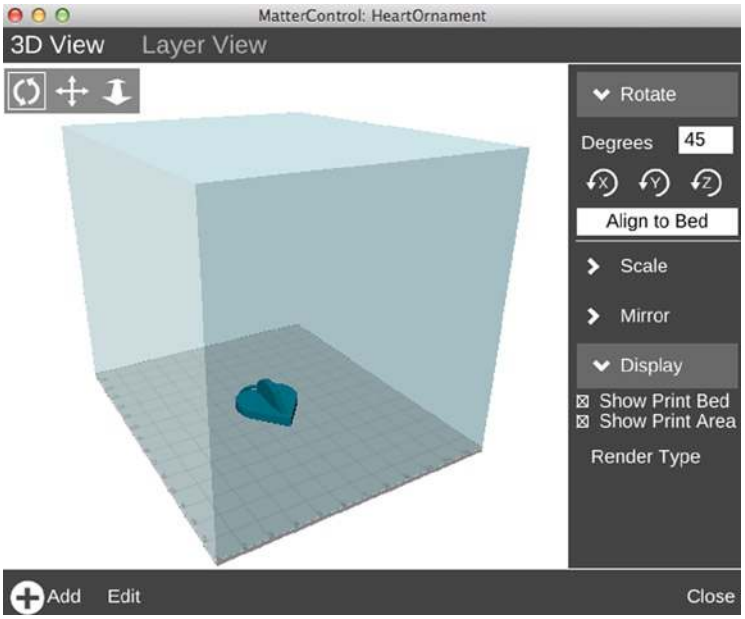


Figure 8-7. *Laying out the heart on the simulation of a real platform*

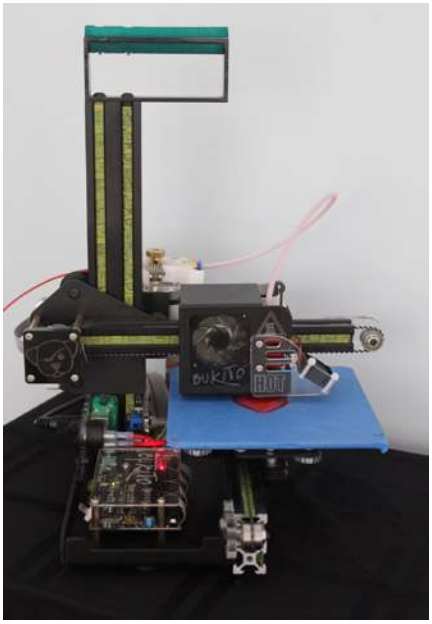


Figure 8-8. *Laying out the heart on the platform on the real printer*

www.it-ebooks.info

Host programs provide a simulation of the layer-by-layer buildup of the model, too, so you can anticipate any problems before you print. Figures 8-9 and 8-10 show the simulation and actual views of a honeycomb infill layer in process.

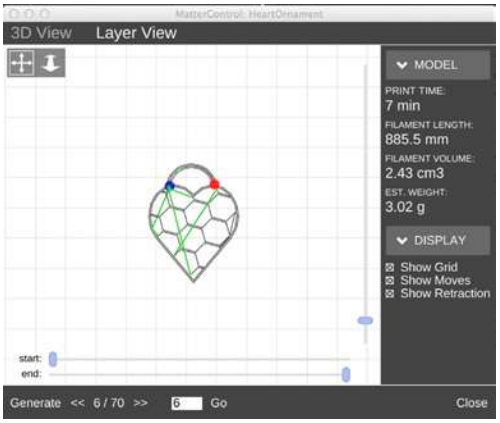


Figure 8-9. *The Layer View simulation of a honeycomb support layer being created*

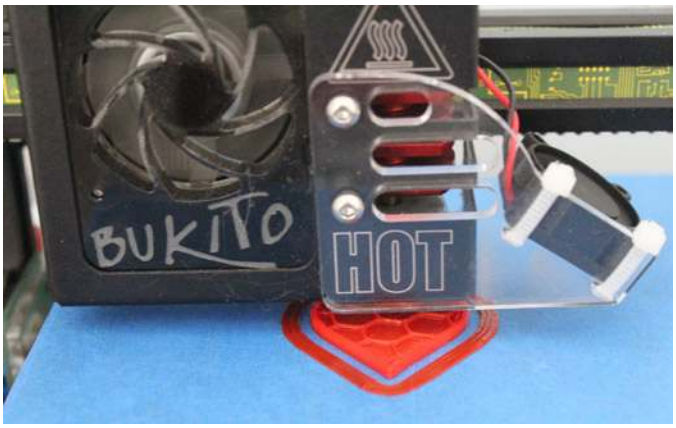


Figure 8-10. *The same thing happening on a real printer, using the same settings*

And finally, the heart will finish! Figure 8-11 shows one on blue tape with its skirt, made with the preceding settings.

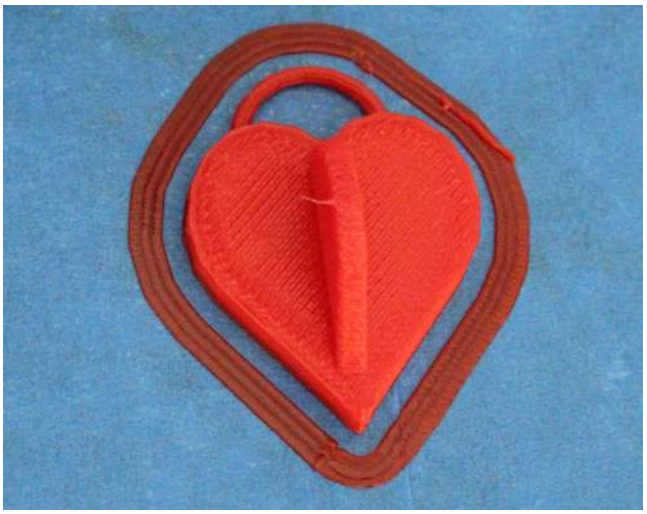


Figure 8-11. *The finished heart*

■ **Tip** If you want to try this heart yourself, create a Tinkercad account and download the STL from the author's Tinkercad files at `https://tinkercad.com/things/9fjmzUPBmR9`.

www.it-ebooks.info

Simple Print Example 2: Abstract Base

You may be getting discouraged that creating each print with all the settings just discussed is going to take forever. The reality is, though, that you will create a few standard groups of settings and will use those over and over. To make this point, next we will create an object that is actually fairly simple to print, but looks like it should need support. We will use exactly the same settings as we used for the heart pendant to create this piece.

It's an elegant abstract base (something that you could stand a little statue or art piece on) designed by Metalnat Hayes of Deezmaker. He used Blender to create it and uses it frequently as an eye-catching 3D printer demonstration.

Figure 8-12 visualizes how the piece will appear on a Bukito platform. Figures 8-13 through 8-15 show different layers as we approach the top. Figure 8-16 shows it partially built, similar to Figure 8-14, and Figure 8-17 shows the finished item.

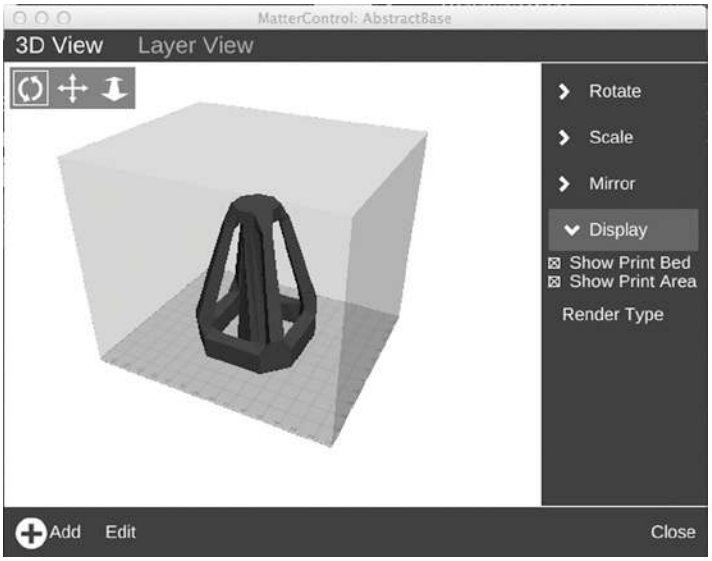


Figure 8-12. *MatterControl 3D view of the piece as it will appear on the platform*

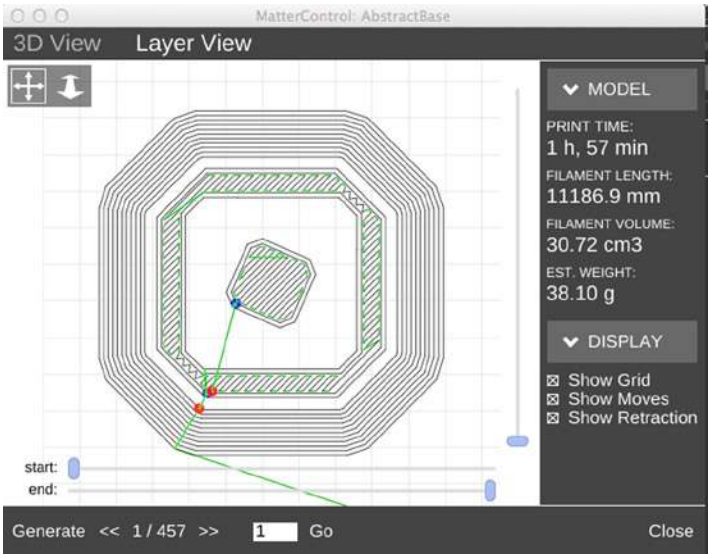


Figure 8-13. *MatterControl visualization of the first layer*

www.it-ebooks.info

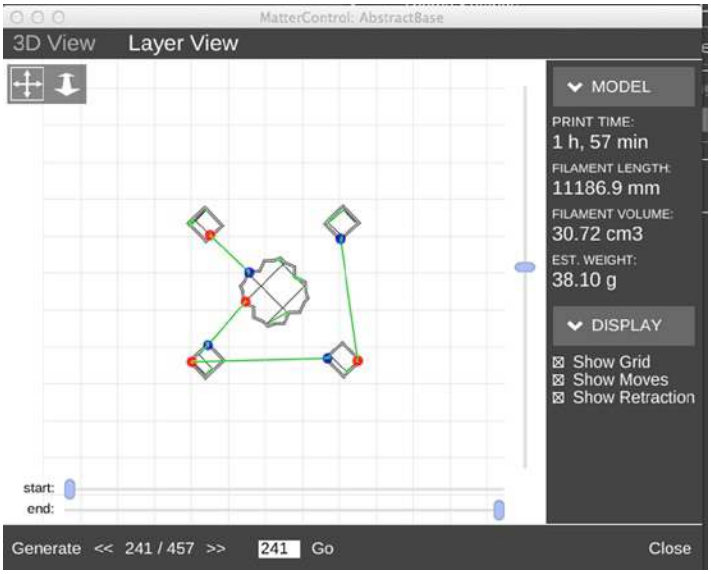


Figure 8-14. *MatterControl visualization of a layer partway up*

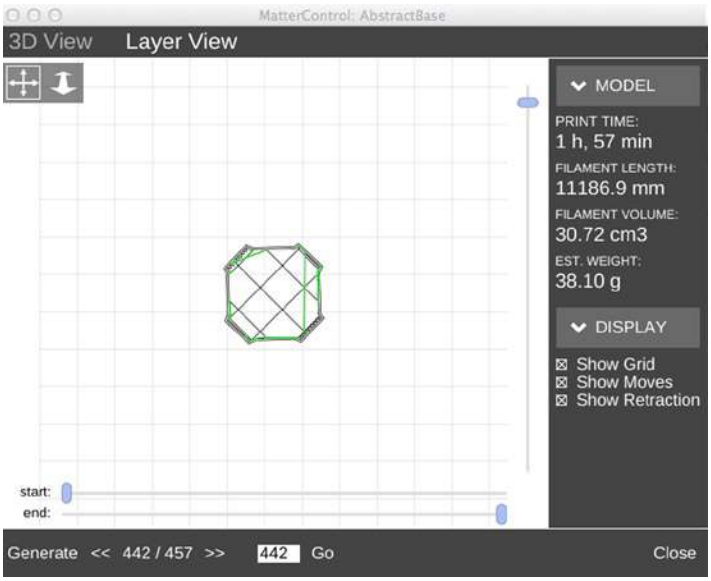


Figure 8-15. *MatterControl visualization of a layer near the top (note layer count at bottom)*

www.it-ebooks.info

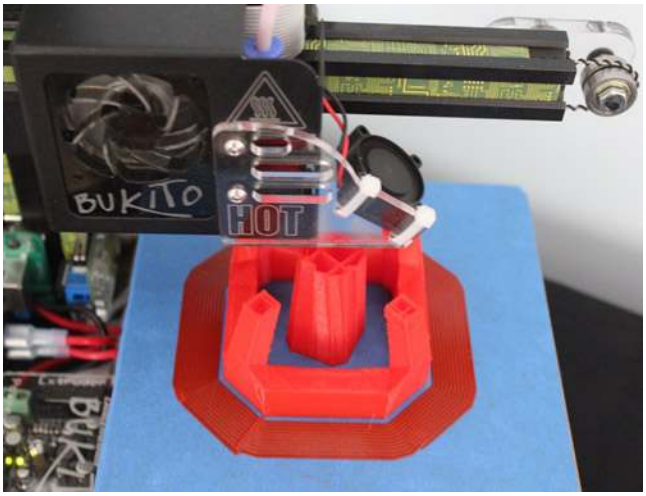


Figure 8-16. *The real thing, partway done; note the grid infill*

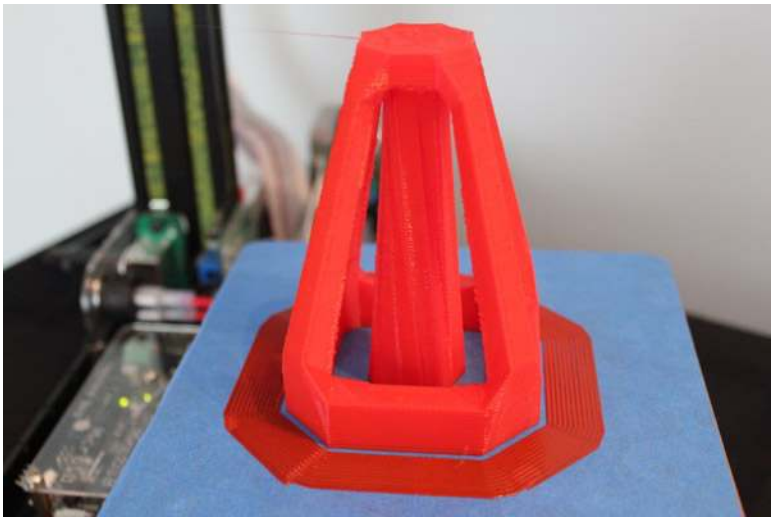


Figure 8-17. *The final piece, in PLA on blue tape (with skirt)*

Printing a Vase

STL files include just the surface of an object. When you create a model, the CAD software wallpapers the surface of the object you created with triangles. Normally, slicing software will automatically create infill to fill in the area inside your object to support it internally.

But suppose you want an object to stay hollow, with an open top, like a vase? Slic3r and Cura both have settings for number of top layers and number of bottom layers. If you set the number of top layers to zero, then there will not be a top layer. If that top layer was all that needed support, then the program will not generate any support inside the vase either, and voila—you have your vase. If you specify a nonzero number of top layers when you have selected Spiral Vase, the slicing programs ignore the top layers.

www.it-ebooks.info

Taking this a step further, if you want to control building up the vase in the vertical direction so there is no visible seam in your delicate vase, you can use the Spiral Vase setting under Print settings, as shown in Figure 8-18. Spiral Vase creates the object by spiraling up from the base rather than by stepping up in discrete layers. The vase walls are just one layer thick with this setting, which can be fairly delicate. Whether a "vase" made in this way will hold water is an open question!

Figure 8-18 shows the settings to create a very simple, small vase (maybe good for one shamrock?) in OpenSCAD (see Chapter 4 for more on OpenSCAD). The entirety of the code is this line:

```
linear_extrude(height = 50, convexity = 10, twist=60,center=true,scale=0.8) square([25,20]);
```

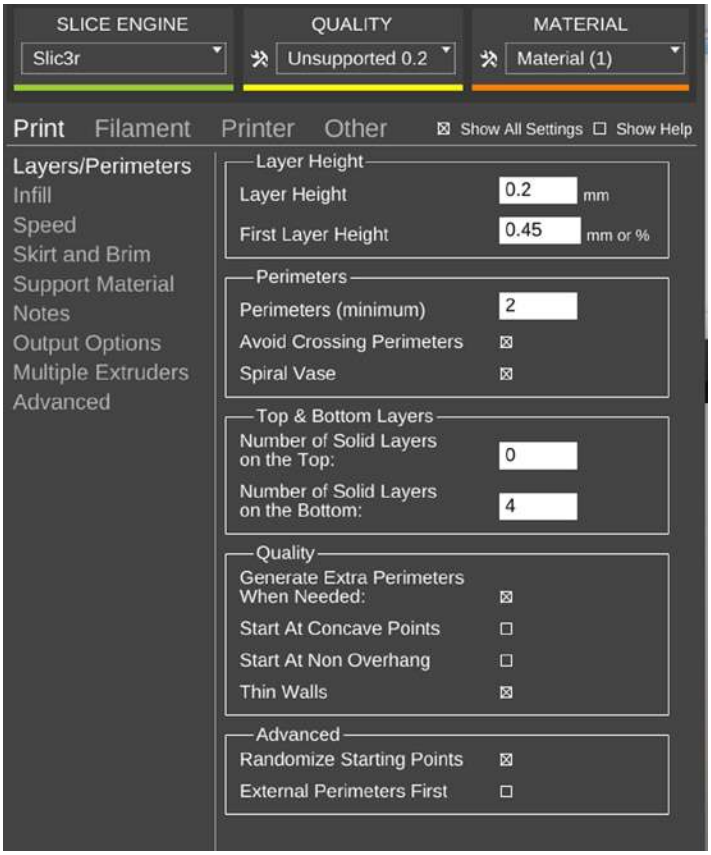


Figure 8-18. *Selecting vase settings in MatterControl; otherwise we used the same settings as for the simple objects*

Figure 8-19 shows the resulting vase, printed in PLA.

www.it-ebooks.info

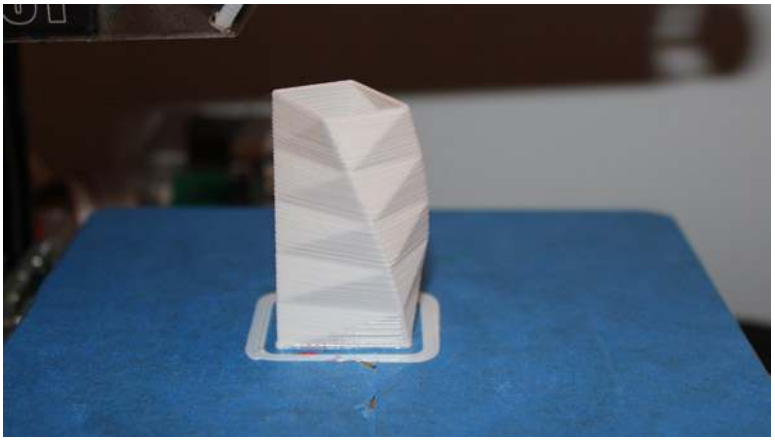


Figure 8-19. *The resulting mini-vase*

Printing a Complex Object with Fine Detail

Some objects are so complex that slicing can take hours, either because the shape is complex or there is a lot of fine detail or both. In those cases, changing a few settings can speed up the generation of the G-code file, with a little bit of risk that the structure will suffer.

A *gimbal* is a support that allows something to pivot freely about an axis. According to Wikipedia, the inventor of the gimbal is lost in the mists of time; gimbals have long been used on board ships to isolate items from the rolling motion of the waves or to maintain the upright position of an item from the effects of rolling waves. An example of this is the three-ring gimbal designed by Diego Porqueras in Solidworks, shown in Figure 8-20.

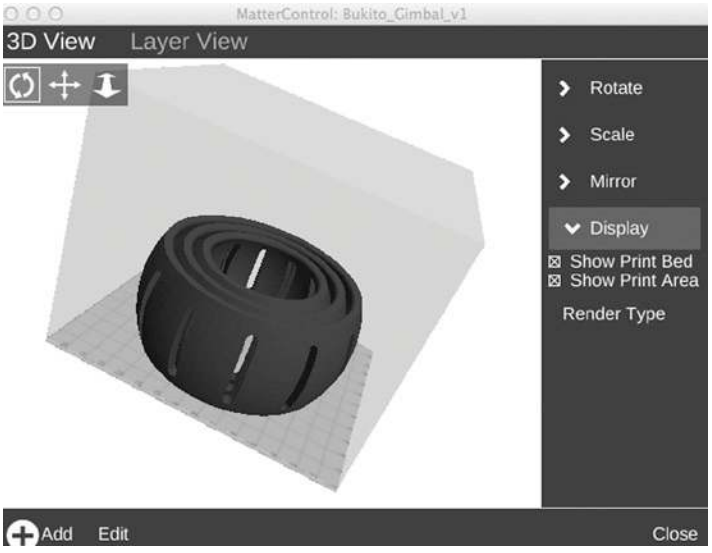


Figure 8-20. *A three-ring gimbal*

www.it-ebooks.info

■ **Tip** If you want to try this gimbal yourself, download the STL from Youmagine at www.youmagine.com/designs/bukito-gimbal-demo-print.

This gimbal works by having small protrusions on the rings with corresponding holes in the other rings. Slicing this object without some prior thought can result in very, very long slicing times. However, a few minor adjustments can reduce the time to a reasonable period. There is a setting called Avoid Crossing Perimeters under Print, then Layers and Perimeters in Slic3r. Unchecking this box and the "thin walls" box makes the process vastly faster by reducing the amount of inter-triangle checking the slicing program has to do. If you uncheck these settings, watch your print carefully for a few layers and review the visualizations. Figure 8-21 shows the settings that are changed from the earlier "Simple Print" baseline ones.

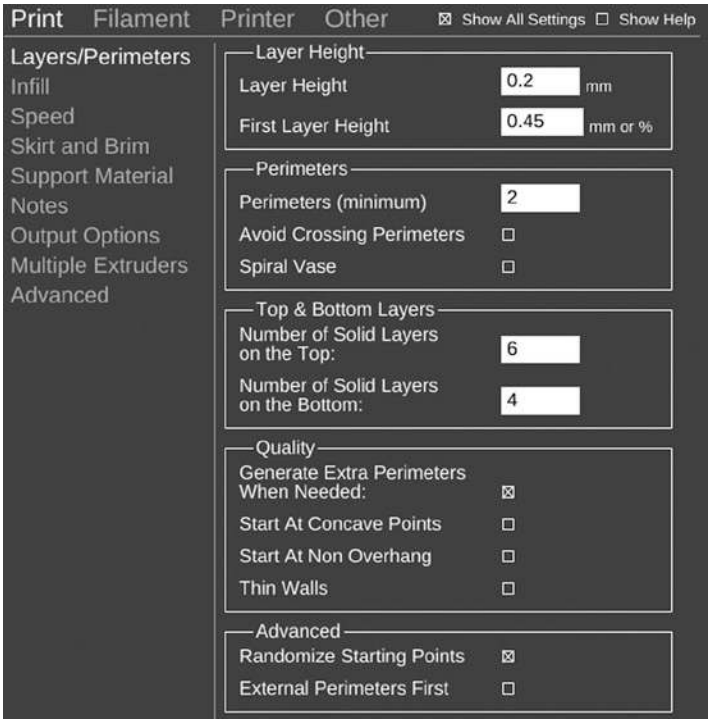


Figure 8-21. *Changes to simple object settings for the gimbal*

A perusal of the layer visualizations (Figure 8-22) shows that some of the layers near the center of the print will have these protrusions. The shells are nearly hollow, with just 12% infill in this case. Figure 8-23 lets you see what this looks like on the printer.

www.it-ebooks.info

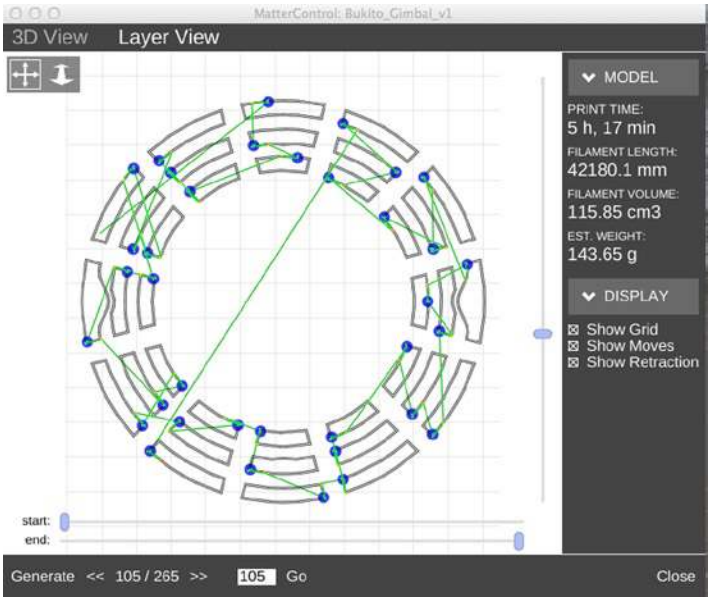


Figure 8-22. *A layer in the region that comprises the gimbal pivots*

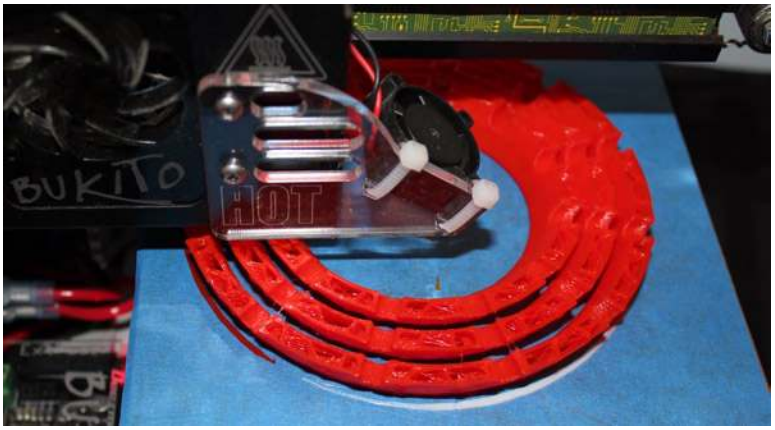


Figure 8-23. *An intermediate layer of the actual print*

The finished gimbal turns about two axes, as shown in Figure 8-24.

www.it-ebooks.info

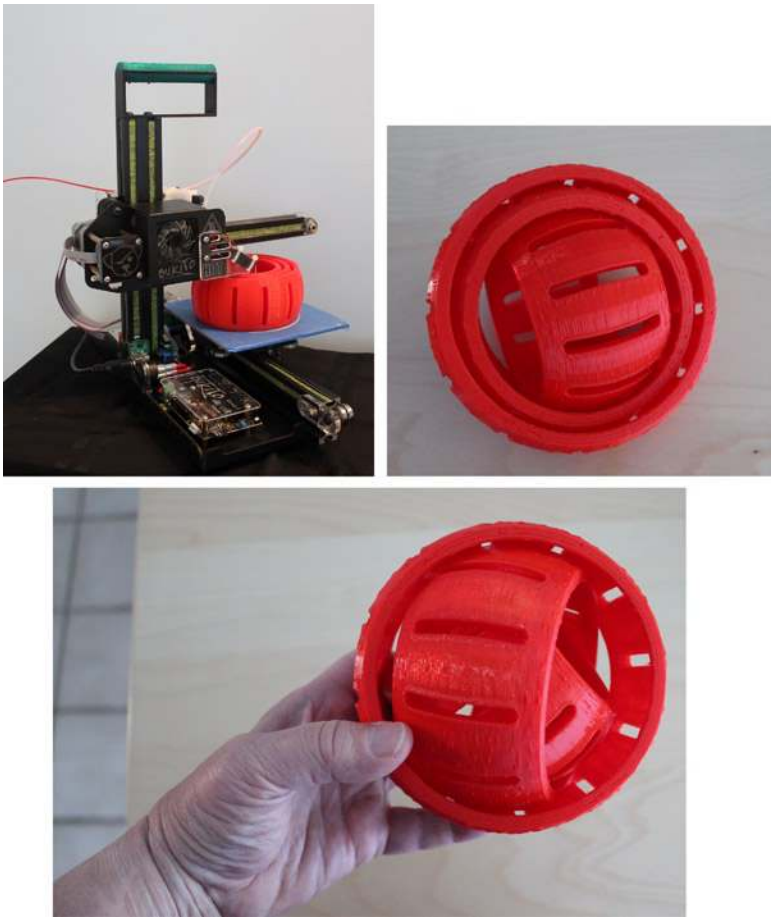


Figure 8-24. *The finished gimbal on the printer; it moves freely about two axes*

This print could have very easily been impossible without a bit of thought. If the pivots had been tiny, thin ones instead of the gradual, curved ones you can see in Figure 8-22, it would have been very difficult to print. The decorative holes are oriented vertically so that there are small, curved areas to bridge across, and the pivots do not stress the printer's capability. Avoiding long, skinny protrusions parallel to the build plate or small protrusions in general raises the likelihood of a successful print.

Printing with Support

In Chapters 4 and 5 you saw a variety of examples using a bear that required support to print correctly (unless it was cut in half). We tried various angles in Chapter 5; here we will put the bear on his tail to see how that works out. Figure 8-25 shows MatterControl's visualization of the bear on the platform in this orientation.

www.it-ebooks.info

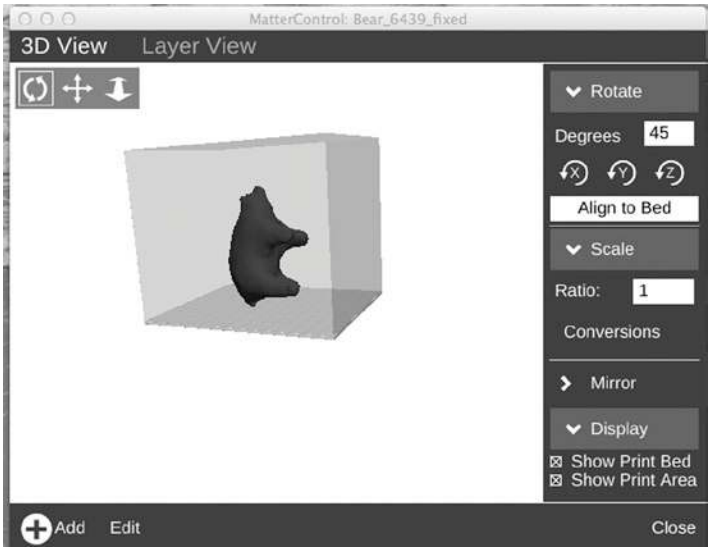


Figure 8-25. *The bear on the platform, tail down*

The support structure will need to support the bear's rear and his front legs. Figure 8-26 is a cross-section partway through the build that tells us that there will be two bars of support (the two smaller cross sections) in addition to the bear itself.

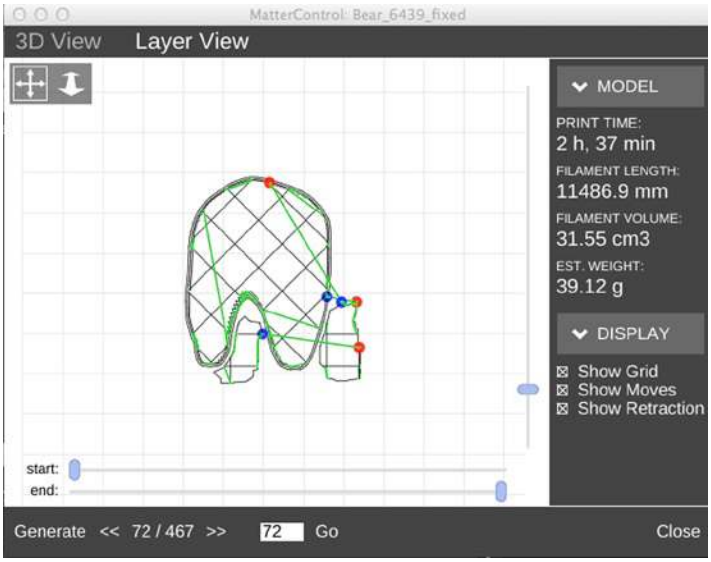


Figure 8-26. *A typical layer showing a cut through the main part and the support*

www.it-ebooks.info

Generating basic support is straightforward; you tick the box labeled Generate Support Material under Print Settings and then Support Material in the slicing program, as shown in Figure 8-27. We set the Overhang Threshold angle where support starts to be generated to 45 degrees. (Refer back to Chapter 5's section about support for details about overhangs.) This time we used the MatterSlice slicing engine to see if it will be different from the previous Slic3r attempts with this piece.

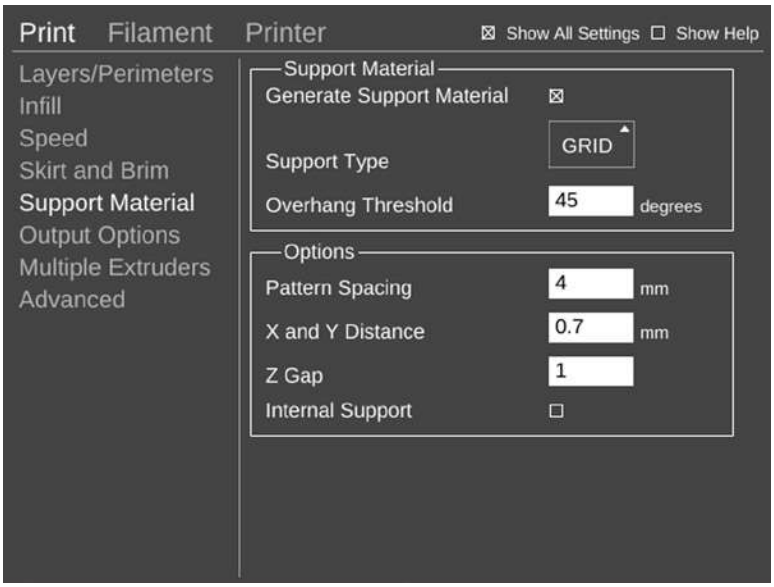


Figure 8-27. *MatterSlice support settings used in this example*

The next two figures show the bear building up. First the program creates a wide skirt (Figure 8-28), the support for the rear of the bear. Because only the tip of its tail actually touches the platform in this orientation, the initial layers are more or less all support. Then in Figure 8-29, we see the bear partially finished, with the columns of support under where his front legs will be. Note that these pillars of support are the smaller, cross-sectioned areas in Figure 8-26.

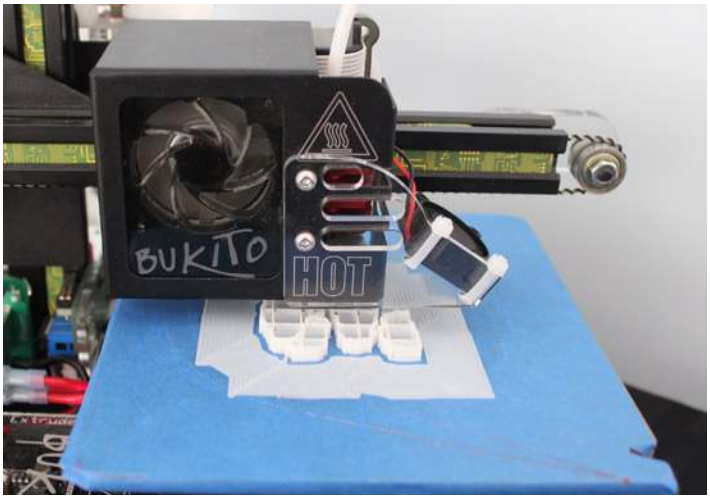


Figure 8-28. *The first (nearly all support and skirt) layers of the bear*

www.it-ebooks.info

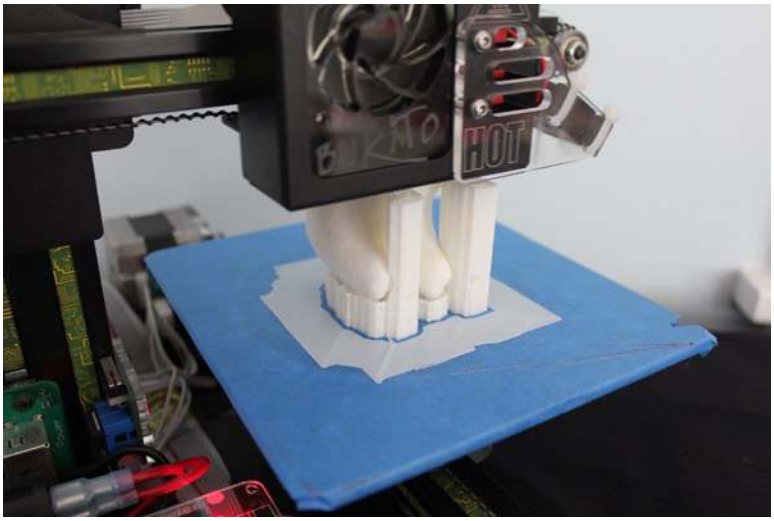


Figure 8-29. *The bear's support starting to build up*

When the bear is complete (Figure 8-30), it has three areas of support: one under the tail, and one under each front leg. The front leg ones will snap off relatively easily. This time we used a different slicing engine than we did in the previous chapters, but we also used a different orientation. Sometimes a bit of experimentation will reveal that certain pieces of software handle certain cases better than others.

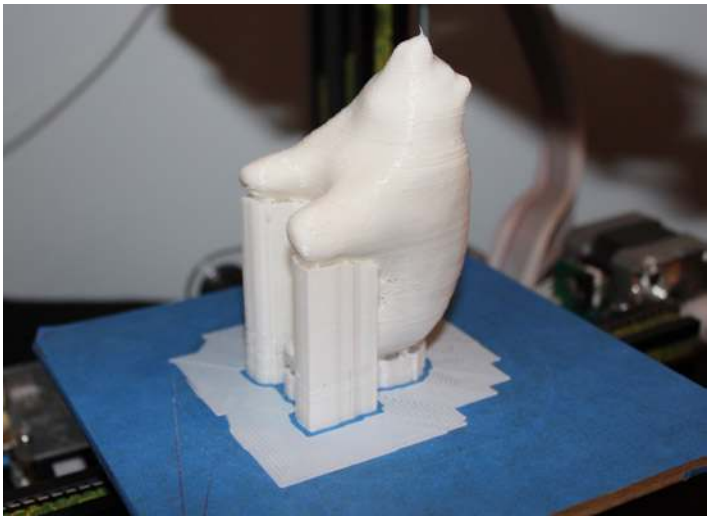


Figure 8-30. *The completed bear and support*

www.it-ebooks.info

■ **Tip** Some objects have particularly awkward support needs. For example, the Herreshoff cleat historic nautical reconstruction project in Chapter 12 needs support under its protruding parts parallel to the ground, but really does not need support in some hollow enclosed areas.

Cura has a setting that only places support such that the support touches the build platform and does not build support between parts of the print. This can be handy in these cases and can avoid hard-to-remove unnecessary support. Use these settings with care, though, if you have large openings that might be difficult to bridge across.

Hand-Building Support

Sometimes a model's geometry only requires support in one place (for example, just one long protrusion, like an outstretched arm or hand). In those cases, the slicing programs might decide that you need support in all kinds of places. An alternative is to figure out some minimal support yourself and create a small object or two that you place underneath the problem area to hold it up, just as you would stick a folded-up piece of cardboard under a too-short table leg.

You can use any of the programs from Chapter 4 to create a rectangular solid (or more complex piece) to tuck under the problem area. Then you can add this piece to the build platform in either Repetier Host or MatterControl right along with your primary piece and tuck it under the problematic piece. Make sure that this piece (which is a 3D-printed project in its own right) has enough of a base so that it does not just fall over, and design it so that it is easy to snap off the primary piece. This is rarely necessary, though, and is a last resort if the existing tools just will not work for you.

Dual Extruders

A printer with dual extruders allows you to print in two colors or two materials. Exactly how this works depends a lot on the dual extruder machine in question, but this general guide will give you some ideas on how to get started with your machine. You can use a dual extruder machine in two ways. First, you can use a dissolvable support material in one extruder so that you can just wash off support. Alternatively, you can print in two materials or two colors. We will look at each of these.

■ **Note** This section was originally written by the author of this book for the Deezmaker Bukobot Wiki. You might check there for any updates and examples of duo prints at www.bukobot.com.

Dual Extruders: Using One Head for Support Material

If you are printing something with significant amounts of support material, you can use dissolvable support. In this case, you can use the regular Repetier Host interface to slice your model. You need to change the Slic3r Printer settings to two extruders and set the support material to be one of the extruders.

■ **Caution** You will need to tell your slicing program some details of your dual extruders, most notably how much they are offset from each other. Your manufacturer may have told you this, or you may need to deduce it. The process for deducing this on Deezmaker printers is outlined at www.bukobot.com, which might give you some ideas if you do not have any information on a dual extruder printer that you happen to have acquired.

www.it-ebooks.info

Dual Extruders: Models in Two Colors (or Two Materials)

When you are printing models in two colors (or two materials), you need to follow a somewhat different process than you did for one-color printing. You need to create two STL files that are interleaved into an .AMF (additive manufacturing file format) file. Note that any rotation needed when arranging the files for printing has to be done in the STL file generation, because this process does not allow for any rotation in Slic3r.

You also have to split your model into two STL files so that there are no places with structure created with both colors trying to occupy the space. If something penetrates something else, there must be a hole in the one object to accommodate the second, just as in physical space. The following exercise explains this in more detail.

The steps, then, go like this:

- First, generate your STL file in two parts, but interleaved as they will be in the print.
- In OpenSCAD, for example, if you plan ahead that you are developing a file for two extruders, you can add ! in front of a structure to include only the structures included in that structure, and * at the front to exclude a particular structure. Figure 8-31 shows this code in *OpenSCAD* before anything is separated out for two extruders.

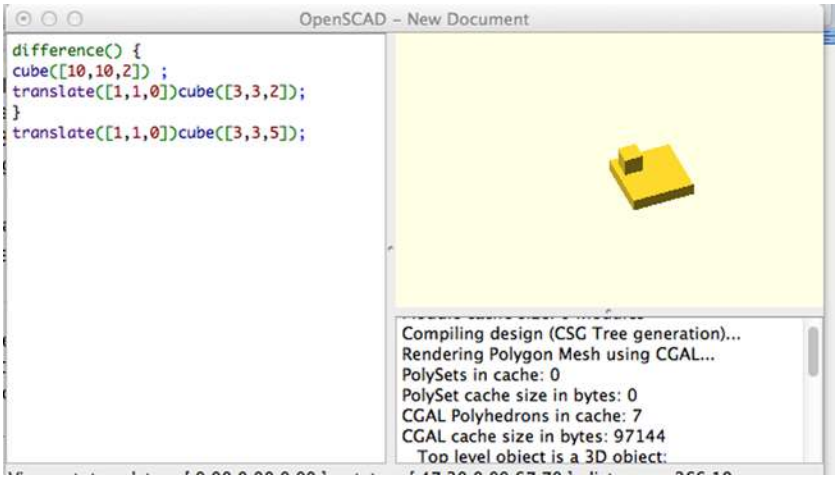


Figure 8-31. *OpenSCAD code for this example*

Change the code as shown in the following snippet to export the larger square with a hole in it and export that first STL file (note exclamation point ahead of `difference`):

```
!difference() {
        cube([10,10,2]) ;
        translate([1,1,0])cube([3,3,2]);
}
translate([1,1,0])cube([3,3,5]);
```


www.it-ebooks.info

■ **Note** This example as described here has coincident faces and could have resulted in a non-manifold mesh, particularly in older versions of OpenSCAD. This example went through slicing and printing without issues. If you wanted to make absolutely certain that you would not have to clean up some non-manifold faces later (as described in the section on watertight and manifold models in Chapter 5's discussion on slicing a model using Slic3r in Repetier Host), the cube being subtracted should extend past the faces of the one from which you are subtracting it. However, this means that you cannot use the simple, symmetrical process explained here. If your slicing software complains about a non-manifold edge, go back and extend the piece you are subtracting a little so that it does not exactly lie on a face.

Change the code to look like the following (adding an exclamation point ahead of `translate`) to output the smaller box that will penetrate the larger one, and then export the second STL file that will make up this object:

```
difference() {
          cube([10,10,2]) ;
         translate([1,1,0])cube([3,3,2]);
             }
!translate([1,1,0])cube([3,3,5]);
```

After this exercise you will have two STL files. To slice the files, you have to use Slic3r itself, not a host program. Here is the process:

- Bring up Slic3r, and in the File menu select Combine Multi-material STL Files. Bring in the files and then click Cancel when you have brought in both files.
- The Filament setting on top is for Extruder 1.
- The program will create a file ending in `.amf.xml`, which combines the two. Set your Print, Filament (for both extruders) and Printer settings. Then click Export G-Code to get your G-code.
- To print your piece, go into a host program and import the G-code you just made. Run as normal.
- If your model needs support, in your Slic3r settings under Support you can decide which extruder's material you want to use for support. This material will be used throughout the model, even to support materials from the other extruder.

Figure 8-32 shows how the box within a box code in the preceding example turned out on a Deezmaker Bukobot Duo. Note that this process in Slic3r generates the little wall around the piece visible in Figure 8-32, called a full-height skirt. It's intended to wipe off the extruder between colors on each layer. Cura follows the shape of the layer rather than making a constant-width wall and thus builds a sort of wrapper that has to be cut off but is a more efficient use of filament.

www.it-ebooks.info

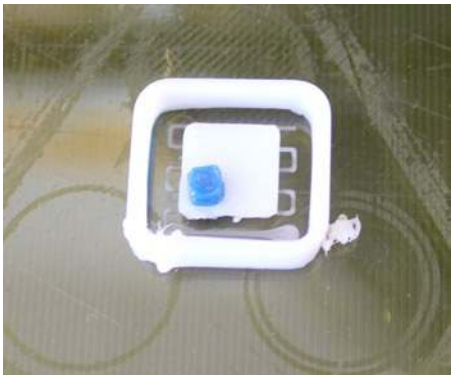


Figure 8-32. *The small dual extruder test on a Kapton tape platform, printed in two colors of ABS on a Bukobot Duo*

Be sure you rotate the entire model before exporting from the program you are building in (here, OpenSCAD) because the combination file, in Repetier Host as of this writing at least, does not allow rotation.

■ **Tip** If you are using a dual-extruder 3D printer to print two colors and, on top of that, support is needed, you will need to pick one of the extruders to do the support for both materials.

Speed Settings

You probably noticed that there were many speed settings under the Print category. By and large, as a beginner it is best to set these to your manufacturer's specifications and then leave them alone. However, if you start printing with more exotic filaments (see Chapter 7), you may want to slow down the print. Experts also often adjust the first layer speed downward to ensure that the first layer has the best possible chance of sticking. If your prints are not sticking, slowing down the first layers might be a technique to try.

Adjusting speed is still largely an empirical exercise with consumer open source printers, and with experience you will begin to see what types of print your particular printer might have trouble with and thus might benefit from a slower print. Slowing down a print does have its issues, though. There's the obvious one of lowering printer throughput if you are using your printer to complete a project on deadline, so you may not want to just keep cranking down the speed unless it looks like the only option.

Summary

This chapter has tied together the material in Chapters 4 through 7 by walking you through some examples. These examples detailed the settings that you would use for prints similar to these circumstances. A few standard combinations of settings should serve you well for most of your projects; learning when you need to get more creative is knowledge that will come with experience.

Next you will learn more about what to do with your print after it finishes printing, with an explanation of some metal-casting processes and some post-processing techniques in the next few chapters. After that, we will get into some applications and predictions for the future—always a dangerous exercise in the fast-changing world of 3D printing.

www.it-ebooks.info

PART 3

3D Printing Meets Traditional Prototyping

By allowing designers, architects, and similar professionals to envision their creations, 3D printing makes the early part of the innovation process a lot more efficient than it used to be. The three chapters in this part show you how desktop 3D printing can be used as an enhancement to (or replacement for) more-traditional prototyping or small-batch-manufacturing processes. These chapters emphasize the "shop class" side of 3D printing, whereas Part 2 emphasized more of its computer lab aspects.

Chapter 9 describes how to use a 3D print as a starting point for a one-off cast metal part. Printers that print directly with metal are likely to be out of consumer reach for a while, but with a little knowledge and planning, you may be able to visit a foundry with your 3D-printed part and use it to get a metal one made for you.

Chapter 10 gives you some ideas about how to do larger real-world projects using a consumer-level 3D printer. You may want to print something big or paint your object or make the print surface smoother. This chapter gives a lot of practical advice on creating professional-looking objects with a hobbyist-level printer.

Chapter 11 wraps up this part with some suggestions on how to figure out what is going wrong when your printer just is not cooperating or when you need that last gnat's eyelash of performance out of it.

www.it-ebooks.info

CHAPTER 9

Moving to Metal

It is possible to 3D print in metal starting with a powder that is fused (*sintered*) by a laser or glued with a binder. As of this writing, this remains a very expensive process, and these are not desktop consumer printers. However, there are ways to move from a 3D print in plastic to a cast metal object relatively cheaply. 3D printing can make traditional prototyping processes faster and more efficient.

This chapter goes through the highlights of two common techniques for casting metal parts: sand casting and lost-wax investment casting. The intent here is not to teach you how to do metal casting; you will need more than a book chapter for that. However, if you learn about the process and the issues that arise during casting, it will give you some ideas about how to create a print that will cast successfully. The end of the chapter goes over some techniques to create prints that are more likely to work well, and looks at the tradeoffs between direct metal printing versus printing in plastic and then using traditional casting.

The Sand-Cast Process

The sand-casting process is very old, and its origins are lost in antiquity. It is still used today in many applications, from one-off casts through mass manufacturing. In brief, one creates a *pattern* in some material such as wood, clay, or wax (and in this chapter, PLA). The pattern is a positive mold of what you want to cast in metal. Then sand infused with a binder is packed around the pattern. Channels for pouring molten metal are carved to the pattern, and the pattern is extracted. Molten metal is then poured into the empty space where the pattern was, and the final metal piece is extracted from the sand when it is cool enough.

In this section we will sand cast several pieces you have seen in previous chapters: the Leopoly bear, printed in halves without support (refer to Figures 4-8, 5-3 through 5-5, and 8-25 through 8-30); the simple heart pendant (Figure 4-2 and the first example in Chapter 8); and a model of a classic boat that you will hear a lot more about in Chapter 12's discussion about using 3D printing to teach history. The boat model (Figure 9-1) was created from plans of a classic boat from the Hart Nautical collection of the MIT Museum, and the design is used in this chapter courtesy of the MIT Museum. Diego Porqueras took the plans, recreated the boat in Solidworks, and then printed it in PLA.

Figure 9-1. *William Hand, Jr. historic half-hull boat (see text for credits for this and other uses of the boat in this chapter)*

www.it-ebooks.info

Foundry artisan Peter Dippell cast all the sample pieces in this chapter. The author would like to thank him for teaching her about the process, casting the samples, and allowing her to photograph it all. The sand used here is a substance called Petrobond, which is more or less regular sand mixed with some oil. It is rather spectacularly messy but holds fairly fine detail well. The process here is at the artisanal level; sand casting is used as an industrial process in many industries. There's no reason, though, that 3D printing can't be used to make small-batch patterns for this type of casting, versus the one-at-a-time process shown here. At the end of the chapter we will discuss the possibilities.

■ **Caution** The material in this chapter is intended to give you an idea about how an experienced artisan can create a metal piece based on your 3D print. It should give you enough information to create a part that will cast well. It is not a do-it-yourself guide to casting, though. You need to know more about safety procedures and equipment, which you should learn directly from an experienced artisan.

Sand-Casting Terminology

Sand casting has its own terminology, which we will use in the rest of this section. Knowing their language may help you communicate with the foundry, so we will start with a glossary of sand-casting terms. There are a lot more terms out there and some usage inconsistencies among industries, but these will get you started:

- *Pattern*: The model (3D printed, in this case) of your final part.
- *Parting compound*: A substance used to keep sand from sticking to the pattern. With the materials used in this example, the parting compound is a powder that is the analog of dusting a pan with flour before baking.
- *Flask*: The metal frame that holds the sand in place around the pattern.
- *Riddle*: A strainer-like device to shake sand over the pattern without lumps.
- *Bench rammer*: A big mallet used to pound down the sand in the flask.
- *Strike-off bar*: A long bar used to smooth the sand across the top of the flask and wipe off any excess.
- *Drawscrew*: A screw threaded a short distance into the pattern, with most of it sticking out. It is used as a temporary handle to lift the pattern out of the sand when it is time to pour in the metal.
- *Basin, sprues, runners, and gates*: The sprues are channels that metal flows through to reach the mold, and also is what the excess metal that winds up solidifying in those channels is called. There is some inconsistency in different fields about how these words are used precisely, but generally the *basin* is the channel where the metal is poured in. Smaller channels that lead right into the mold cavity (where the pattern was) are called *runners*. The point where a runner enters the mold cavity is called a *gate*. Sometimes all of this plumbing is just referred to as the *sprues*. The metal parts that harden in the channels are typically called *sprues*, too.
- *Draft*: Introducing a slight taper on some surfaces to make a cast easier to pop out of the sand.

www.it-ebooks.info

Patterns Made from PLA

Pieces to be cast are called *patterns*, and we will call them that for the rest of the chapter. The images that follow show the process of sand casting the patterns in Figure 9-2. These pieces were all printed in PLA without any special planning for this process, except for a little bit of gentle hand-sanding for some of the pieces.

Figure 9-2. *The PLA patterns used for the items in this chapter. Note the pins in the bear's lower half*

In Figure 9-3, the boat pattern is on a piece of wood at the bottom of the flask (the ring of metal that will contain the sand) and coated with parting compound. The coating ensures that the pattern will come out of the sand easily later on.

Figure 9-3. *The boat pattern in the flask*

www.it-ebooks.info

Filling the Flask with Sand

Next the flask needs to be filled up with sand, as shown in Figure 9-4. It's important that the sand lays smoothly on the pattern, so rather than just pile it in, the sand is passed through the riddle. The riddle is essentially a giant, coarse strainer. The sand is mixed with oil in this example—a compound called Petrobond, which is rather expensive given that it is really just oily sand.

Figure 9-4. *Pushing sand (mixed with oil) through the riddle into the flask*

After the initial layer of sand is put in the flask through the riddle, we fill the rest of the flask with a small shovel. Then the sand is pounded down with the bench rammer (Figure 9-5) and the excess pushed off with the strike-off bar (Figure 9-6). Finally, a piece of wood is placed on top, and the whole thing is flipped upside-down (Figure 9-7 before the flip, Figure 9-8 after). The flask always rests on a piece of wood called a *backing board*, so that the sand does not fall out. The oil makes the sand slushy so that it will hold a shape better than you would think possible, unless you grew up making impressive sand castles.

www.it-ebooks.info

Figure 9-5. *The bench rammer packs the sand around the pattern*

Figure 9-6. *The strike-off bar gets rid of the excess sand in the flask*

Figure 9-7. *Getting ready to flip the flask upside-down*

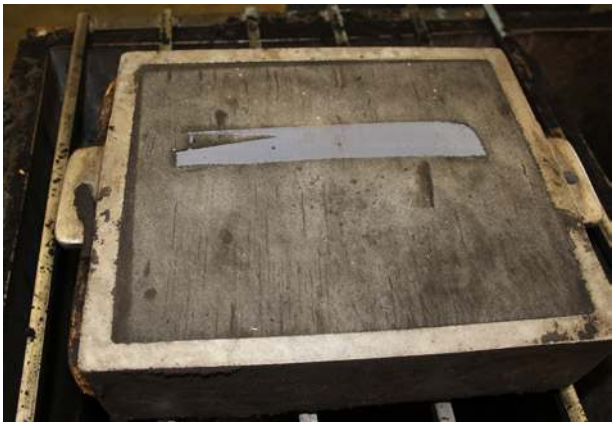


Figure 9-8. *The pattern in the flask after it has been flipped upside-down*

There are many different types of parting compound, depending on the "sand" and other aspects of the process. In this case, a light powder in a bag dusts what was the bottom of the pattern to prepare it for the next steps (Figure 9-9).

www.it-ebooks.info

Figure 9-9. *Using parting compound on the "bottom" of the pattern*

The half-hull boat pattern we are working with is pretty flat on one side, but we still need to form what will be the bottom of the finished piece. To do that we will add the upper part of the flask and fill it with sand, too (Figure 9-10). The process here is similar to filling up the first part of the flask: running the initial layers through the riddle to make sure the sand touching the pattern is smooth and then filling in the rest with a small shovel and pounding it all down to make it smooth. (3D printer prints made on a consumer printer should almost always have an appropriate large, flat surface anyway to keep them attached to the build platform during the 3D printing part of the process.)

www.it-ebooks.info

Figure 9-10. *Getting ready to fill in the rest of the flask*

Once the top half of the flask has been filled with sand and pounded down, it will have picked up an impression from what was the bottom of the pattern (Figure 9-11).

Figure 9-11. *The pattern and its impression on the top half of the mold*

www.it-ebooks.info

Cutting Sprues and Runners

The next step is cutting the basin, sprues, runners, and gates—channels for the hot metal to run through from where the metal enters to the hollow mold cavity where the patterns used to be. In principle, we could have 3D printed the sprues, too, but we did not do that here. We talk about why not later in the chapter. To make the entry-point sprue (sometimes called a gate), we dug out a hole in the top half of the flask. We used a spoon to get things started (Figure 9-12) and then a tapered, hollow tube called a *sprue cutter* (Figure 9-13) to cut a clean, cylindrical hole.

Figure 9-12. *Getting the entry sprue started*

Figure 9-13. *Making a good, clean, circular hole*

Once a basin is set up, it's time to carefully lift off the top part of the flask again, and carve the channels that will take the liquid metal from this entry point into the mold cavity that will be left when we remove the pattern. Sometimes these final channels are called *runners*, or are just referred to as sprues, too. In Figure 9-14 we see the carved-out sprues, which were just created with fingers and spoons in this case. The runners should be positioned so that they are not inserted at a critical point of the pattern, because they will need to be cut off at that point later on.

www.it-ebooks.info

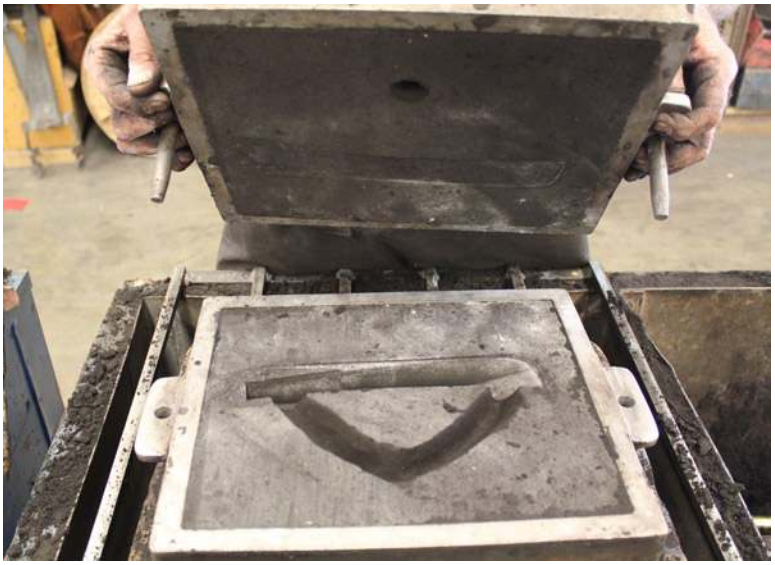


Figure 9-14. *Cutting the rest of the sprues*

This pattern is relatively simple because it has a flat base and no overhangs. (We will see that a lot of the characteristics like a flat bottom and no overhangs that make a 3D print simple translate into the moldmaking world as well.) A more complex print (like the bear) can be done as shown in Figure 9-15. Each half of this pattern has to be pulled out separately, but the initial alignment is done with some small pins on one side and holes on the other.

Figure 9-15. *Setting up a part to be cast from a two-piece pattern*

www.it-ebooks.info

Once these channels are set up, the pattern is carefully removed with the drawscrew. The top of the flask is put back on, and the flask is ready for molten aluminum. The molten metal (here, aluminum) will enter the sand through the sprue we carved out in Figures 9-12 and 9-13 and then continue on through the runners and finally into the hollow created by the pattern (Figure 9-14).

Pouring in the Metal

Aluminum melts at 660 degrees C, so substantial equipment is required just to get it molten and to handle the metal safely. Good protective clothing is a must, too. Pouring in the metal results in a lot of smoke and some flame because some of the oil in the sand burns off in the extreme heat.

Heating up the metal and skimming off undesirable impurities is a process in and of itself. Figure 9-16 shows what this looks like right after the metal pour for two flasks put one on top of the other. (The bottom flask is on a piece of wood; the top one counts on the sand of the flask below it to keep in the sand.)

Figure 9-16. *Two flasks with molten aluminum cooling*

Finishing the Sand Casting

After a few minutes go by, the metal will have cooled enough to take out of the sand. When the flask is opened up again (Figure 9-17), we can see how our boat now has an additional piece—the sprues, which will we will have to cut off later.

www.it-ebooks.info

Figure 9-17. *Hot aluminum boat and sprues come out of the mold*

The next step is to pull the piece out of the sand with tongs, shake off the sand, and then wash it off and cool it down further with water. Figure 9-18 provides a better view of the boat and its sprues. In Figure 9-18, you can just see the sprue that went back toward the top of the flask (it's behind the triangular sprue in the foreground). The sprues will be cut off later on with a hacksaw or machine tools after the piece has cooled a little more. You can go back to Figure 9-1 to see what it looks like when the sprues have been cut off and the whole model cleaned up.

Figure 9-18. *The boat and its sprues*

Planning Ahead for Better Casting

The pieces that were cast in this chapter were taken directly from other examples in this book in the interest of end-to-end continuity. However, in practice, if you were printing with an eye to casting the output, you would want to optimize the end-to-end process to have the best possible output. This section looks at a few other pieces we have printed in other chapters of this book to see what the problems would be if we just cast them as-is.

www.it-ebooks.info

We took the simple heart pendant (Figure 9-19) and Leopoly bear (Figure 9-20) as referenced at the beginning of this chapter and cast them, too. Both of these castings had some issues which could have been prevented with a little planning.

Figure 9-19. *Heart patterns and finished aluminum cast pieces*

Figure 9-20. *The bear, cut in half as in Figure 5-5, in PLA (two pieces) and aluminum (one piece)*

www.it-ebooks.info

Adding Draft to Patterns

Good pattern-makers use a bit of *draft*. Instead of having vertical surfaces intersect horizontal ones at right angles, surfaces that would have been vertical instead are tapered a bit to facilitate removal from the sand. In this case, it would have helped to have a little bit of draft (just a few degrees) rather than the crisp verticals everywhere. Right angles can be printed by well-made 3D printers, but in sand casting the sand tends to get stuck in corners and edges and result in some imperfections. As you can see in Figure 9-19, the place where the vertical half-heart pokes upward is a little rough at its base because of the sharp edge there in the 3D-printed version.

■ **Tip** Engineering-style CAD programs (like Solidworks) have the ability to add draft to an object. It is difficult to do with beginner programs, however. If you are doing serious work that you want to be able to cast, you may need to step up to one of these more industrial-strength programs.

Avoiding Undercuts

An *undercut* in the mold-making world is the equivalent of an overhang in 3D printing. It is a part of the model that (in this case) would pull out sand when the pattern is pulled out. In Figure 9-20 we can see the bear that we printed in two halves in Chapter 5 (Figure 5-5) cast as one piece. As we saw earlier in Figures 9-2 and 9-15, each of the two halves went into half of the flask, with pins holding together the halves. In this case, there wasn't a lot of care taken during the cutting-in-half process to be sure that there were no overhangs right near the cut (there was—the bear's nose) and also that the pieces printed perfectly (the platform might not have been absolutely flat, or small imperfections could have been introduced in various ways). This resulted in the pieces having some undercuts and some gaps between the model halves at noticeable places, like the nose and tail.

Just as it is difficult for the printer to create an object that does not build up smoothly from the platform, it is hard to sand cast an object that cannot be pulled out of the mold smoothly. If a mold is made up of two pieces, those pieces also have to fit perfectly, with appropriate tolerances. As mentioned in the previous section, higher-end, engineering-oriented CAD programs have tools to separate parts for 3D printing and subsequent casting with the types of considerations noted here.

Layer Orientation

For the most part it will be natural to print an object in the same orientation that you would cast it because, as we saw in the bear example, many of the same considerations apply. However, objects tend to be strongest in the direction perpendicular to the layers, and so an object may pull out of a mold best and be strongest if it is printed at 90 degrees from the orientation in which it would be cast. (In the case of the bear, this would mean printing it on its tail, as we did in the discussion about support in Chapter 8.) This may require more support and thus more scarring of the original 3D print, though, which would require cleanup before or after the casting. This 90-degree layer orientation may also be preferable because the *x/y* resolution of a print is typically much higher than the layer resolution (smoother detail can be produced on side surfaces than on top surfaces), and because the rounding of the edges of the layers creates a very tiny undercut between each layer and the previous one.

Shrinkage and Clearances

Because metal contracts when it cools, your finished cast part will be smaller than your 3D printed part was. Be sure to account for this. You can look up the shrinkage for a particular material (usually stated as a percentage) for your material and plan your 3D printed part a little bigger, if your cast part needs to fit into something else precisely.

www.it-ebooks.info

Think through *how* precisely parts need to fit together; don't make holes exactly the same size as the objects that need to fit into them. A little experimentation may be required to engineer your process end to end.

■ **Tip** There are some good manufacturing engineering textbooks that might be helpful to get a good structured overview if metal casting and working with metal is new to you. One of the classics of the genre is *DeGarmo's Materials and Processes in Manufacturing* (Wiley, 2011) by DeGarmo, Black, and Khoser, with new editions appearing regularly.

Printing Your Sprues?

Sand-cast patterns traditionally have been carved out of wood or another material that would survive the required number of uses. Because traditional patterns are used multiple times, being able to re-print them isn't as much of an advantage as it is in investment casting. There, the pattern is lost each time (more on that in the next section). However, the sprues and runners need to be re-created each time in sand casting.

With careful thought (to avoid lots of support and other additional work), it might be possible to print these sprues and runners as well. Depending on your comfort with your chosen CAD program and its capabilities, it might or might not be easier for you to figure out how to make an STL file with the appropriate plumbing in addition to your main model. Bear in mind, too, that whoever casts your model will need to extract what you build from the sand, which might get tricky if you also want to avoid support.

It is worth thinking through whether your geometry might lend itself to some process shortcuts such as printing your sprues and runners, and to confer with whoever will be casting your piece about whether some time might be saved by printing some or all of the sprues and runners.

Investment Casting

Sand casting is very versatile, but it is not good for capturing fine detail or for pieces that have complex geometries, such as a sculpture of a person. For that type of work, investment casting, sometimes called lost-wax casting, can be a good fit. With those advantages comes additional complexity. Investment casting has more steps and for high precision can take a lot longer than sand casting. Professional sculptors producing bronze statues typically use investment casting.

There are a lot of variations, but fundamentally the process goes like this:

- A piece is carved in wax. Typically, sprues are also carved in advance and attached to the piece so that there are strategic paths to flow in metal and to allow air to escape.
- This wax piece is then coated with several layers of ceramic or plaster, or alternatively a plaster cast is made around it.
- The plaster or ceramic is allowed to harden.
- The wax is "burned out" (melted away, hence the name, since the pattern is lost each time) leaving the plaster cast.
- The hollow mold is filled with metal.
- The ceramic mold is broken open, and the piece is removed and cleaned up.

One common variation (used for making a copy of an existing sculpture) is to make a mold of the existing sculpture. Then *that* mold is filled with wax, and the process continues as before, starting with creating the sprues.

Obviously lost-wax casting is very laborious, particularly if the wax piece has to be carved over and over. This is where 3D printing has a role.

www.it-ebooks.info

Lost-PLA Process

Wax has been used for the investment casting process for centuries because it burns out at a relatively low temperature and leaves a clean mold. As it happens, PLA has similar properties. Although the term has not yet entirely caught on, some people in the 3D-printing community have referred to using PLA in place of wax in lost-wax as a "lost-PLA" process. You cannot carve PLA, but you can definitely print multiple molds to melt out. Some moderately priced resin printers use materials that are wax-like.

The sculpture in Figure 9-21 was created by Peter Dippell using a "lost-PLA" process. The story of the piece went like this:

- The subject was scanned with a 3D scanner (Chapter 4).
- This created an STL file (Chapter 5).
- The STL file was then converted into G-code (Chapter 6) and printed in PLA on a consumer-level printer.
- Sprues were added to the PLA piece.
- A plaster cast was poured around the sprued piece, taking care that there were no bubbles in the plaster that would cause imperfections.
- The cast hardened, and the PLA was burned out.
- Molten aluminum was poured into the mold.
- After a bit of cooling time, the cast and aluminum were thrown into a bucket of water.
- The mold was then broken off, and the statue extracted.

Figure 9-21. *An aluminum, investment-cast statue of Rich Cameron (this book's technical reviewer)*

www.it-ebooks.info

In Figure 9-21 you can still see the 3D-printed layer lines. Whether this is a big problem or a charming reminder of where the piece was "born" is in the eye of the beholder. One can look at it as the "brush strokes" of a new medium! Alternatively the piece could be sanded lightly before casting, or the piece could be polished at this point. However, sanding or polishing risks losing some of the very detail that investment casting seeks to preserve.

Casting vs. Printing in Metal

So, why not just print in metal in the first place? As mentioned earlier, printing in metal is expensive, although some research work is underway to make it less so. The commonest technique is to have a fine powder of metal, sometimes with a binder, and to fuse it via one of several means. Typically the binder (if any) is then removed by heating the part. There is research work at the moment to characterize how strong these materials are, predict when they are likely to fail, and so on. But these techniques are new, and it will take time to understand them fully. Printing metal can also be dangerous. The fine metal particles used in these processes can be abrasive, extremely flammable, and explosive; traditional casting has its own issues, but they are perhaps more obvious.

The advantages of taking a 3D print from a desktop filament printer and casting it traditionally are, first, the cost, and second, that it is a smaller step from existing processes. The second point is also a minus—it *is* a smaller step, and less of a dramatic breakthrough than pure metal printing will be once the issues are worked out. But in the meantime, it is a potentially cost-saving parallel option. You also need to take into account the surface finish smoothness you require and what the minimum-cost method is to achieve that.

Finding Casting Services

If you want to cast a part in metal, search for "metal casting" or "investment casting" and your city name in your favorite search engine. You can also see whether your local community college or high school has a jewelry design program; if it does, the program likely knows of a small-batch casting service or may offer the service for a fee themselves. You can also talk to a shop teacher at your local high school or the people at a makerspace to find an artisan. Visiting a Maker Faire (`www.makerfaire.com`) is probably a good way to network, too.

Professional foundries may or may not be comfortable using PLA in their investment casting workflow because it is not a medium they have used before and they may have evolved proprietary formulations they do not want to change. They may want to do the intermediary step of taking a mold from the 3D print and then burning out their wax as usual.

■ **Tip** If you want to create an STL file and print in metal in the first place, there are service bureaus that will create metal-printed parts for you. You can find a service bureau for printing in metal by searching for "3d printing metal services." Service bureaus that can print metal usually publish *design rules* that explain what they can and cannot do (including material properties, feature size, maximum part size, and so on). Some service bureaus also let you publish your design and let others print it. There are many evolving business models in this space.

Summary

In this chapter you learned about options for taking a 3D-printed part and using it to create a metal one via traditional manufacturing processes. The chapter reviewed the process of sand casting and investment casting so that you know how to create a 3D-printed part to use as the front of the casting process. Finally, we explored how you might find casting services or a service bureau to let you print in metal directly.

www.it-ebooks.info

CHAPTER 10

Large Prints and Post-Processing

For many applications, a part works fine as soon as it comes off the 3D printer, perhaps after picking off a bit of support. However, there are circumstances that require a bit of post-processing, either because the part had to be made in multiple pieces or because it needs to be smoother than the printer can achieve.

This chapter describes how to deal with a model that is either computationally big (an STL file over 50MB or so) or that, if printed, would be physically too big to fit in a printer's build volume in one pass. This chapter also covers how to lower the resolution of an STL file to make it more manageable. You saw how to divide a model in software back in Chapter 5's section on avoiding support by cutting a model into pieces. The purpose is different here, but the process is the same. In this chapter we will talk a bit about gluing together the parts after the print is done.

A printer will also leave behind layer lines, scars from support, or the odd bit of stringing across open areas. This chapter also talks about how to post-process a model by sanding, painting, dyeing, or chemically smoothing it.

3D printing is a bit of a crossover discipline; it's part computer science and part shop class. Any one person may not come into the field comfortable with both aspects. If you are entering this space from the software side, team up with a shop teacher, a sculptor, or someone else who routinely builds real physical objects. The techniques in this chapter are likely to be familiar to them.

Printing Computationally Complex Objects

Sometimes the 3D model of an object is very complex, even if it is specifying a physical print that fits comfortably into the build volume of a printer. For example, this issue arises in some scientific visualizations, as we will talk about in Chapter 13's discussion of 3D-printed models of complex molecules. It is tempting to want to keep all the detail, but the reality is that a consumer-level printer will probably not reproduce detail of a very complex model anyway.

If the model is going to be both physically big and very complicated, cutting it into pieces and slicing and printing those pieces separately can lower the STL file sizes of the pieces to plausible levels.

Tip An STL file more than a few tens of megabytes is probably too big both for most slicing implementations to handle and for most printers to reproduce. About 50MB is a practical limit—less if you run the slicing programs on an outdated computer. For a larger file, consider the two techniques discussed in this section.

---

www.it-ebooks.info

If you find yourself with an STL file that is too big to work with, you can use the MeshLab program to re-mesh the model with fewer triangles. MeshLab is available at http://meshlab.sourceforge.net and is discussed in several places in Chapter 4. MeshLab is a powerful program but can be a little daunting to navigate because of its terminology. Because it is open source, it can change at any time, but as of this writing the following process will re-mesh an object:

- Open MeshLab and import a "mesh" (i.e. your STL file) under the File menu.
- Then click Filters ➤ Remeshing, simplification and construction ➤ Quadratic Edge Collapse Decimation. (You can see the issues here with somewhat non-intuitive menu items for the new user!)
- In the dialog box that pops up you can try cutting the number of surface triangles relative to what the default displays and experiment with the percentage reduction (from no reduction to 100%). A value of 0.5 will cut the number of triangles in half. You can see what you can get away with based on how the rendering in the program looks. If you have lost an unacceptable amount of detail, don't save the new mesh; import it again and start over.
- When you like the result, you can export a new STL file.

Alternatively, you can cut the file into pieces as described in Chapter 5 and then glue together the physical pieces after they are built. You will learn about that in the next section.

■ **Note** Cutting a file into pieces to reduce the file size (rather than to reduce the dimensional size) will reduce the amount of data that the slicer needs to process, but it can still result in a G-code file with segments so short that they will execute in significantly less time than it takes to transmit and process them. This will result in the firmware slowing down or even pausing between segments, and these unexpected speed changes will result in print artifacts. Printing from an SD card rather than over USB mitigates these issues, because reading G-code from the SD card is faster than transmitting it over the USB connection. (Thanks to Rich Cameron for this point.)

Printing Physically Big Objects

Consumer-level 3D printer build areas are for the most part relatively small, because it is a lot harder to manage temperature control and precision of the build platform and the rest of the machine's structure. As a result, most consumer printer build areas are under 200 mm or so in any dimension, and many are way under that. This means that if you want to build something bigger than that, you are going to have to cut the object into pieces in software, print the parts, and then somehow construct the final object out of those pieces.

If you want to print an object that will not fit within the build volume, you can cut it into pieces. For example if the object is long and skinny, you can cut it into a few objects that you can then arrange on the build platform and print all at the same time. Otherwise, you will have to print the object using multiple runs. In either case, you will need to glue or assemble the piece afterwards.

Objects That Are Too Long for the Build Platform

If you have a long, skinny object that will not fit within the longest build dimension of your printer, first check to see whether it will fit diagonally on the platform. You will also want to keep the orientation that will minimize support, so there may be some tradeoffs there. If you are considering printing diagonally in all three dimensions, it may be easier to cut the object in half and later glue two pieces that would both lay flat rather than pick off a lot of support.

www.it-ebooks.info

If you do need to print a thin but long object (for example, a chopstick), you probably will be able to arrange the pieces on the platform next to each other and print them simultaneously. If, for instance, you were trying to print a tall, skinny tower, you could cut it into several pieces, lay out the pieces on the build platform in one or more groups, and then glue the pieces together.

Objects That Are Too Big in More Than One Dimension

If the object you are trying to print is too big in more than one dimension, you will need to split it along two axes—that is, into at least four pieces, with a lateral slice and a horizontal slice. If any parts require particular precision (if there will be critical joints, for instance), consider where your printer has the highest precision and arrange cuts so that those pieces will fall there. In most cases, the best resolution is at the center of the print bed.

■ **Tip** Even when the full part is too large in two or even three dimensions, it may be possible to divide it into just two or three pieces by judiciously cutting and then orienting the pieces. For example, a letter H that needs to be printed slightly larger than the build platform (in both *x* and *y*) can be cut into two halves, each of which may fit diagonally. A pyramid-shaped object that is too tall for the print volume and too wide only in one dimension may be cut into three pieces (the top and two halves of the base). An L-shaped object may be cut into four quadrants, one of which will be empty. Be careful if your printer does not have consistent resolution throughout its build area (most Cartesian printers do). (Tip courtesy of Rich Cameron.)

Chapter 5's section on cutting to avoid supports describes the process of cutting a part in two. To cut into multiple pieces, follow the same process but cut the piece in half and then cut the halves again (or into however many pieces make sense to make the part fit into your printer's build area). The general principles apply. Depending on which program you use to cut up the model, you might be able to slice along several axes at once, or you might have to explicitly make one cut at a time, save the pieces, and then cut them in turn.

■ **Caution** The techniques discussed in the rest of this chapter are more similar to a "shop" environment (or a chemistry lab) than a computer lab environment. If you are not used to this type of environment, work with someone experienced first to learn safety procedures. Use eye protection and gloves, be sure your space is well-ventilated, and follow the chemical manufacturer's instructions.

Gluing the Pieces Together

Once you have printed the pieces, use glue that works on plastics. Cyanoacrylate adhesives ("superglues") work pretty well on PLA and ABS. Nylon is difficult to glue with any adhesive appropriate for home use.

■ **Caution** Before using any glue, read the manufacturer's instructions and use glues in well-ventilated areas. You might want to try out a particular glue on a few scrap pieces first to be sure that it does not discolor your material. Glues may dissolve pieces a bit, which allows the "welding" process described later in this chapter.

---

www.it-ebooks.info

Using an Acetone Slurry

If you are printing in ABS, there's another alternative for adhering pieces to one another (but see the Caution that follows). Acetone will melt ABS and so can be used to weld one piece of ABS to another. Some people put a little bit of acetone in the type of bottle used for nail polish (ones with a small brush) and add the skirt, support material, or other scrap from the print. The acetone will dissolve the scrap into a slurry that will weld the pieces together without melting the edges of the print too much. Or, if precision edges are not important, you can use a drop of acetone to bond the parts together. We will talk about using acetone to smooth a print later in this chapter.

■ **Caution** Acetone is flammable and volatile. Its vapor is invisible and heavier than air. The vapor can pool if you are in an unventilated area and cause a fire or explosion. Use it in a well-ventilated area without open flames or sparks. Follow the cautions on the manufacturer's label.

Acetone welding only works for acetone-soluble plastics, such as ABS, MABS, HIPS, and polycarbonate. Most other 3D printing filament materials (such as PLA and nylon) are not acetone-soluble. Some PLA formulations (depending on additives) may partially melt, whereas others have been known to warp and crack when exposed to acetone.

■ **Tip** When you paint acetone on a part, the acetone evaporates, and you will get a bit of condensation from the air. This can make the surface of the object a bit cloudy (you will see this in Figure 10-2). If you are just "welding," then clouding does not matter, but if you are smoothing (described later in this chapter as *chemical smoothing*), it is an issue. On the other hand, if the acetone is too warm, the surface will bubble. Keeping the acetone at about 50 degrees C (120 F) works well. You can put your acetone nail-polish bottle in a shallow bowl with an inch of warm water in it. If your printer has a heated build platform, you can set your heated platform to 50 degrees and put the (glass) bottle on it (see "Manually Controlling Your Printer" in Chapter 6). *Never* microwave acetone or ever place it anywhere near a stove; an explosion or fire can result.

Sanding, Chemical Smoothing, Painting, and Dyeing

Filament-based 3D printers will always produce fine layer lines in printed objects. You can think of them in one of two ways: as inherent in the medium (like brush marks on an oil painting) or as a problem that needs to be resolved. If your application falls into the latter category, this section gives you some ways to get rid of those lines and to color your printed part other than by choosing colored filament. We will talk about sanding and chemical smoothing to get rid of layer lines, and then about issues in painting and dyeing finished prints. Thanks go to the good folks at Deezmaker for the techniques in this section.

Sanding

A bit of sandpaper applied gently to PLA prints can significantly smooth the surface. Just use a piece of sandpaper and sand it by hand—any mechanical sanding is likely to melt the plastic. ABS can be sanded but tends to whiten a bit in the process, the same way it bruises when bent. Acetone will reverse this discoloration, so sanding can be used in conjunction with acetone smoothing to reduce layer lines while maintaining sharper features that would be rounded off using acetone alone to remove the layer lines. Nylon just comes out worse than you started if you try sanding it. Figure 10-1 shows a PLA piece being sanded by hand. A sanding block may also be useful, depending on the geometry of the part.

www.it-ebooks.info

Figure 10-1. *Sanding a PLA piece. (This was part of the preparation for sand casting in Chapter 9)*

Smoothing and Bonding ABS with Acetone

In the earlier section "Using an Acetone Slurry," we talked about using acetone to weld ABS pieces together. Similarly, a little bit of acetone can be used to smooth an ABS piece using the same techniques (and cautions!) as those described previously. You may need to experiment a bit to see what works.

■ **Tip** A lot of smoothing techniques available online use acetone vapor and do-it-yourself devices to create and handle the vapor. It is this author's opinion that many of these are unwise and/or too hazardous for the intended general audience of this book; therefore, none of these is described in this chapter.

Do not use acetone on nylon or PLA; nylon will be unaffected by acetone. Unfortunately, chemicals that can smooth PLA are too toxic to be used in a home environment.

Figures 10-2 and 10-3 show an ABS piece (the Leopoly bear we met several times in Chapters 4, 5, and 8) that has been smoothed in places with acetone to remove scars from supports.

www.it-ebooks.info

Figure 10-2. *The Leopoly bear from previous chapters, smoothed with acetone (front view)*

Figure 10-3. *The Leopoly bear from previous chapters, smoothed with acetone (rear view)*

www.it-ebooks.info

As was the case in the Chapter 8 case study, where the bear exemplified a print with support, the bear was printed with his tail down. Because the support was at the back of the legs and under the tail, these were areas where we particularly would want to smooth the printed part. In this case, the acetone was a little cold, though, and as mentioned earlier in this section, the part got a little cloudy at the tail area.

Painting ABS and PLA

You can paint ABS and PLA parts with acrylic paint, like that available in a typical hobby store. If you need a multi-color print and you have a one-extruder printer, painting the object after the fact is a good workaround to produce the colors you need.

Dyeing Nylon

Although 3D-printed nylon may not look the same as it does in fabric form, it will take up dye in a similar way. Nylon filament typically is white, which makes it easier to dye. People have had good luck with household cloth dyes to dye a printed nylon object; check the label on the dye package to be sure that it will work on nylon.

Summary

In this chapter you learned how to work around some of the limitations inherent to the filament-based 3D-printing medium. We covered how to deal with prints that were too complex or physically too large, or that needed smoother surfaces than the printer alone could create. We looked at some suggestions of types of paint and glue to use, and noted some cautions about using chemical smoothing if you are new to the “shop” environment.

www.it-ebooks.info

CHAPTER 11

Troubleshooting

As you have seen in the book to this point, 3D printing is still a bit of an art. To go back to our cooking metaphor from Chapters 5 and 6, you might have a recipe that sounds great and still wind up with a cake that comes out of the pan in ten pieces. The preceding chapters have laid out what can go wrong for many common issues. This chapter covers some more systemic problems that might result from an unfortunate confluence of several smaller problems, as well as problems due to the environment around the printer.

The beginning of Chapter 9 noted that 3D printing requires a little bit of programming knowledge and a little bit of shop class. In Chapters 9 and 10 we cautioned those of you who came into this from the programming side to be a little wary of your limitations. That caution applies in this chapter, too.

However, this time around the reverse is also true: if you came into this as a strong mechanical shop-class wizard, be aware that debugging a system with a lot of software involved is a little different from figuring out what is wrong with something purely mechanical (or even electronic). Be very systematic about keeping track of what you have changed and what was different after you changed it. Otherwise, you may go in circles.

This chapter covers a few common issues that often are caused by a mix of hardware, software, and environmental factors. First, we look at the typical signs of trouble and then cover how to go about analyzing and fixing the problem—or preventing it in the first place. Many of the issues in this chapter are strongly affected by your printer's design, so take any suggestion here with a grain of salt and read your manufacturer's instructions first before taking any advice in this chapter.

Clicking or Grinding Noises

One of the first signs of trouble with a 3D printer is an unfamiliar noise. You will know you are an experienced 3D-printer user when certain noises make you immediately execute a high-speed dive across the room toward your printer. Because prints can take many hours, listening to your printer is often the best way to monitor it (with an occasional glance, of course).

A filament-based printer has to drive the filament into the extruder somehow. Clicking noises usually means that the filament is not going into the nozzle smoothly (or at all). Here are some possible causes:

- The filament might be hung up on the spool or catching on something (see the section "Handling Filament" in Chapter 7).
- The nozzle might be clogged (see the section "Clogged Nozzle" later in this chapter).
- The filament might not have been seated correctly when it was inserted. (This applies at the beginning of a print; if the ticking starts mid-print, this is unlikely.)
- The filament might be too wide to go into the nozzle (check it with calipers as discussed in Chapter 7's section "Filament General Issues").
- Something might be hitting one of the fans on your printer. Check that the fans are clear.

www.it-ebooks.info

Sudden grinding noises usually mean that the print came loose and is jammed under the nozzle. This warrants a sprint across the room to turn off the printer, because the jammed part can exert some unexpected forces on the platform and its supports. Get your printer into a safe condition by stopping the print job. Then manually walk the extruder back out using the techniques in the section "Backing Out of a Bad Situation" in Chapter 6. You may have to re-adjust the build platform (see "Printer Internal Alignment Issues" later in this chapter).

■ **Caution** In addition to being sensitive to abnormal noises, be aware of what a "normal" print run smells like. A burning smell is never a good thing around electronics. Be able to distinguish problems from, say, the smell of ABS printing.

Environmental Issues

3D printers (and 3D-printing filament) are sensitive to drafts, temperature, humidity, and dust. Good printer design can minimize some of the impact of these factors, but you also should be thoughtful about where you put the printer. Some people think of their 3D printer as an item to have in a computer room, whereas others think of it as a machine tool to be kept in a shop. If you keep it in an office environment, you will need to figure out a good way to be certain there is enough ventilation. If you are in a shop, you may have some of the issues noted in the following sections.

Drafts

The 3D-printing process, particularly ABS prints and others built on heated platforms, is very sensitive to drafts. When you arrange your ventilation, do not have a big fan blowing *on* the printer, which may defeat its temperature management. Have the fan pulling air away from the printer—for example, have the printer on a table and a fan on the floor blowing air away. If your ABS prints are pulling away from the platform, check for drafts.

■ **Note** Having a fan blowing directly on the print can improve PLA prints. However, if you are printing it on a heated platform and/or do not have much insulation on your hot end, your printer may need more power to maintain those temperatures.

Some printers optimized for PLA have a small fan to cool the PLA more quickly to improve print quality, but that is different because PLA cooling fans are generally shrouded to keep them from blowing on the nozzle. If the nozzle is well insulated or otherwise shielded, a large fan off to the side can be just as good.

Ambient Temperature

If your printer is in a space that undergoes significant temperature swings, the temperature on the heated bed and/or extruders should still maintain the commanded temperature. However, we have heard anecdotally that very cold rooms and very warm ones have resulted in print-quality issues. If your printer is a true RepRap and has 3D-printed parts, avoid temperatures warm enough to soften the material that was used in the parts. Do not keep a spool of filament (particularly PLA) in direct summer sunlight in a hot parked car.

www.it-ebooks.info

Humidity

Humidity can be more of an issue than ambient temperature. Most filaments are strongly hygroscopic—they absorb water from the ambient air around them. If damp filament is heated, the moisture can bubble and make the filament extrude unevenly, which can cause discoloration and poor inter-layer adhesion. If you live in a very humid climate, keep your filament tightly sealed in a plastic bag with its desiccant when you are not using it. Avoid leaving your printer outside overnight or allowing water to condense on it.

Dust

Is your 3D printer a machine tool or a computer? It is a little of both. If you are going to have your printer in a shop environment, you need to keep the printer as clean as possible. In particular, you want to keep the *filament* as clean as possible so that dirt is not carried down into the nozzle where it will clog it.

If you are working in a dusty environment, you can take a piece of dust-free cloth (a paper towel will do) and use a binder clip to secure the cloth over the filament, as shown in Figure 11-1. The clip should not be gripping the filament; the filament should slide freely.

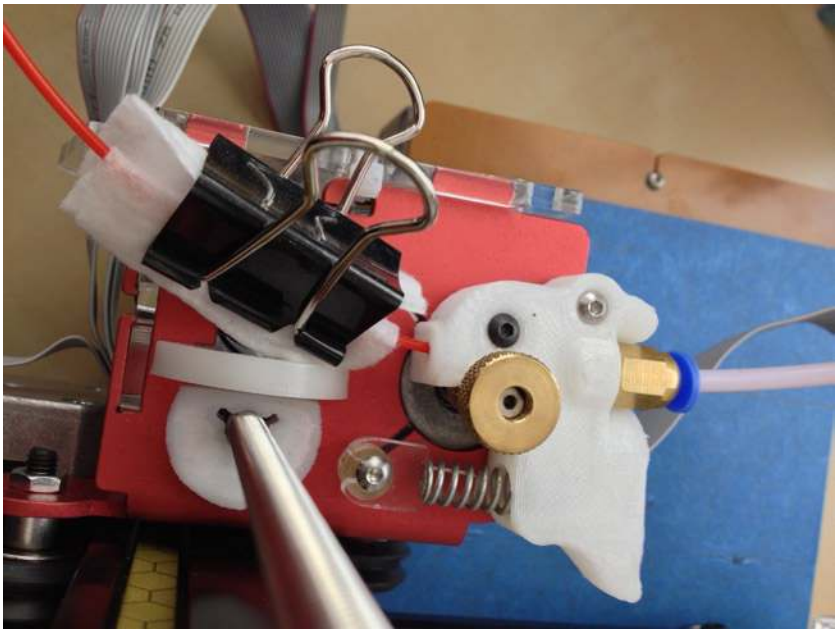


Figure 11-1. *A dust-catcher on the filament*

Be sure the clip and cloth do not interfere with the extruder mechanisms or the movement of filament, or get too close to the hot parts of the printer. The cloth will wipe off the filament as the filament is dragged through by the extruder mechanism. If the cloth gets dirty, you will know you needed it!

The filament will drag the dust-catcher next to the extruder drive. (This printer's drive gear is the round brass object near the center of Figure 11-1.) A dust-free cloth is a particularly good idea if your printer shares space with ceramic, wood, or glass shops, all of which generate a lot of fine dust. Do what you can to keep the printer clean, particularly when it is not in use. If your nozzle does clog, see the section "Clogged Nozzle" on unclogging your extruder later in this chapter.

www.it-ebooks.info

Printer Internal Alignment Issues

A critical characteristic of 3D printing is having the printer's parts align correctly *to each other*. This requires that the printer be both *square* and *tram*. *Squaring* refers to ensuring that the axes are at right angles to one another, whereas *tram* and *tramming* are used specifically to refer to adjustment of the *build platform* to ensure that it is parallel to the *x*/*y* motion of the machine.

A 3D printer that is square but not tram will have the axes at right angles, but the nozzle will not maintain the same distance from the platform as the *x* and *y* axes move. A machine that is tram but not square will usually print fine, but the angles will be wrong so that rectangles will become parallelograms and circles will become ovals. There are several ways in which the printer can get out of tram. For a Cartesian printer to be in tram (see Chapter 2's section on types of printers), the *x,y,z* axes are all square to each other and then the platform is in a plane parallel to the *x* and *y* axes. For other geometries (like Delta machines), this alignment is more complex.

If you suspect that your machine axes are out of alignment because prints that should be rectangles are skewed or the width of an extruded line is not consistent from one end of the platform to the other, first check that the axes are square relative to each other (use a carpenter's square or, in a pinch, any other stiff, accurate rectangular object). If they are not, use whatever adjustments your printer manufacturer provides. Once you have done that, you should check the alignment of the build platform relative to the axes, hereafter referred to as *tramming the platform*.

■ **Caution** Some manufacturers refer to "leveling" a platform. However, do *not* use a bubble level to align your platform. If you have your printer on a table that is not level, but your printer is otherwise square, changing any printer adjustment based on a bubble level would most likely not fix the problem. We use the word *tram* to draw this distinction about internally consistent alignment of the printer axes relative to the platform versus level relative to gravity. Note that the axes are imaginary lines in space; normally, the frame of the printer will be lined up with the axes, but in principle software can compensate if they are not. Be sure you understand what your printer does and does not compensate for before attempting to fix problems.

If the build platform gets out of tram, either you can wind up printing in air in places where the platform is lower than expected or mashing the first few layers on parts of the platform that are too close to the nozzle. Prints that do not stick in one corner and are a bit mashed (with wider-than-normal extrusion lines) on another part of the platform are symptoms of this problem.

A typical way to fix this for most printers is to home the axes manually (see the section "Manually Controlling Your Printer" in Chapter 6). Then take a piece of paper (a sticky note works well) and move your extruder in *x* and *y* over each of the adjustment screws for your platform. For most printers, the piece of paper should be able to get between the platform and the nozzle, but there should be a bit of resistance. There is a device called a *feeler gauge* that does the same thing, but do not use one—a feeler gauge is made of a metal that is harder than your nozzle and might damage it.

As a quick test, you can print a small item with a big skirt (a skirt that is near the edges of the platform) to check platform tram. If the skirt does not lay down evenly, then you need to try again.

Some machines have "auto-leveling" features. For the most part, these cannot allow for the axes being out of alignment with each other, so if your auto-leveling is failing, take a good look at the overall frame geometry and check it with a square if you can.

www.it-ebooks.info

Prints Not Sticking to the Build Platform

Getting a print to stick to the build platform can be challenging. Chapter 7 covered techniques for each type of filament material, and Chapter 8 walked you through some examples of the "right way" to analyze how a print job should be arranged to stick to the platform. However, often failures can be more instructive than success; this section describes in detail an example that does everything the *wrong way* so that you can see the result.

Figure 11-2 is an object that looks like a squared-off tornado created in OpenSCAD. It is designed to fail quickly in mid-print. This design has several problems: it has a tiny contact area with the build platform and slants off at an angle. It needs a raft, or at least a brim, and some support. However, it was sliced without adding any of those things, to create a worst case.

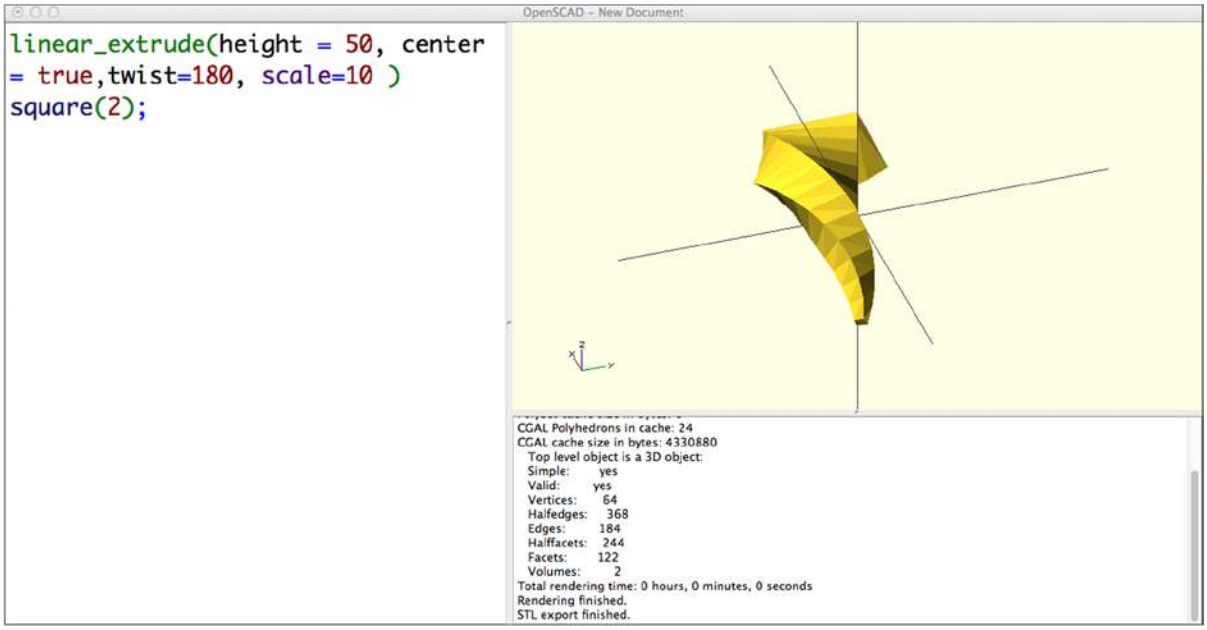


Figure 11-2. *The "designed to fail" print in OpenSCAD*

Figure 11-3 is the result, stopped part way through the print. The "tornado" managed to adhere to the platform for quite a while before it toppled over or was knocked over by the extruder. Then the extruder was printing in air, which created all the stringy stuff. The print was terminated prematurely.

www.it-ebooks.info

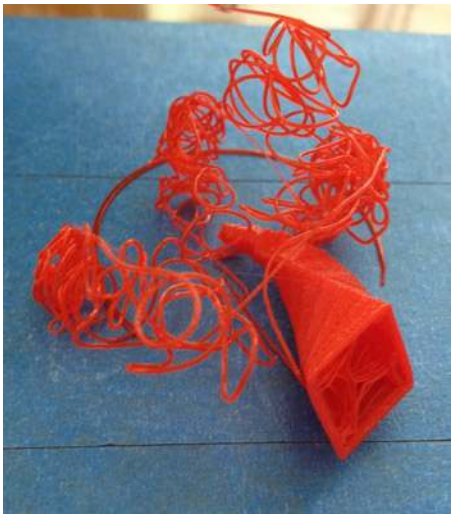


Figure 11-3. *The "designed to fail" print after it was shut off part way through*

If your prints turn out like Figure 11-3, here are some factors to consider:

- Does your print have enough contact with the build platform? (See the "Brims" and "Rafts" sections in Chapter 5.)
- Is your print overhanging enough that either you should build it upside-down (that might have worked here) or build it with support? (See the section "Supporting and Orienting a Model" in Chapter 5.)
- Were you using the right build platform for the material? (Here, we were: this was PLA on blue tape, but the bad geometry overcame the correct settings.) See the appropriate Chapter 7 section for the material you are using.
- Was the platform aligned correctly (as described earlier in this chapter in the section about machine alignment)? If the build platform and extruder are too far apart, the first layer may print in air, and therefore all the subsequent ones have nothing to print on. (This print was created on a correctly trammed machine, but again extreme enough errors in model placement and slicing settings will cause a failure like this. If it had been a tramming issue, the print would not have partially survived as this one did.)
- Were the temperature of the nozzle and the build platform (if it is heated) set correctly? (See Chapter 7's discussions of these requirements for each material.)

If all of these factors check out, consider that the print may not be printable on your machine as-is. It may need support, a raft, or something else to get it to stick.

Clogged Nozzle Solutions

One of the more common problems with a 3D printer is that the printer stops extruding plastic because the extruder nozzle is clogged. The nozzle hole is small and it can fairly easily be blocked with debris that was embedded in the filament, dust, or plastic that got too hot and scorched or burned.

www.it-ebooks.info

■ **Note** The nozzle-unclogging processes that follow are adapted from an online Deezmaker troubleshooting procedure written by Rich Cameron. The original, with any updates since the writing of this book, can be found at www.bukobot.com/nozzle-cleaning. (The photos in Figures 11-4 through 11-7 were taken by Cameron.) Although the instructions there were written for Deezmaker printers, they apply generally for any printer with a nozzle rated to the temperatures suggested here. If your nozzle is not rated to 240 degrees C, you should not use this procedure.

Cold Pull

In the past, the only way to get a clog out of a nozzle was to take the entire hot end (nozzle, barrel, and heater block) apart or take it off and put it in a solvent. Because that is not very convenient, and taking the hot end apart can damage it, the *cold-pull* technique was developed. A cold pull starts with inserting filament in the nozzle just as if you were going to print with the filament.

Instead of using the usual extrusion temperature, though, which would melt the filament, a cold pull uses a lower temperature. The temperature is warm enough to allow the plastic to stretch enough to pull away from the sides of the barrel so that it doesn't seize up entirely, but cold enough so that the filament stays in one piece. Usually, any debris in the nozzle will then come out with the filament. We estimate the best temperature to use for this *cold-pull temperature* in the following description.

The cold-pull technique works best with printers that have polished-smooth stainless steel nozzle barrels. It also works for nozzles that have a polytetrafluoroethylene (PTFE) internal coating. The cold-pull technique has been successfully done with ABS (cold-pull temperature of about 160–180 C). PLA is much more difficult to work with, but a cold-pull temperature of 80–100 C will sometimes work. Nylon 618 filament (pull temperature of 140 C) is far easier and more reliable to use for this purpose due to its strength, flexibility, and low friction. The cold-pull technique works like this:

- To begin, remove as much of the plastic that you've been using as possible. To do this, you can attempt a cold pull with ABS or PLA with the temperatures listed previously.
- Next, heat your nozzle to 240 C so that it can thoroughly melt the nylon and push the nylon filament in. Attempt to extrude the nylon slowly. Most clogs (especially those caused by accumulated dust) will not actually block the nozzle entirely, but will be pushed into the nozzle and stop it when the nozzle pressure increases and then float up out of the way when left to sit.
- If you do not have a hard clog (usually a solid foreign particle lodged in the nozzle), a slow, pausing extrusion should allow you to purge the old printing material.
- Once nylon starts coming out of the tip, you can begin cooling your nozzle to the pull temperature. See Chapter 6 for information on manually controlling your printer to see how to extrude some filament by hand.
- Finally, pull the filament out of your printer manually, if your printer mechanism allows it, or by retracting it using a host program.

■ **Note** The temperatures specified in the preceding list are maximum temperatures—temperatures above which the plastic is unlikely to come out solid. For best results, you should always pull the plastic at the lowest possible temperature, and it may help to cool the nozzle well below this temperature and then continually attempt to pull it as the nozzle heats up again.

www.it-ebooks.info

Figure 11-4 shows some examples of cold pulls. If you pull the nylon out and the surface is rough, dark, discolored, or has black spots around the sides, this indicates that there is residue of overheated or carbonized, burned plastic in the nozzle. If you see this, you should clip off the end and repeat the process until the nylon comes out smooth, clean, and mostly white. Figure 11-5 shows similar examples from with a nozzle that was clogged with overheated plastic, rather than burned plastic.

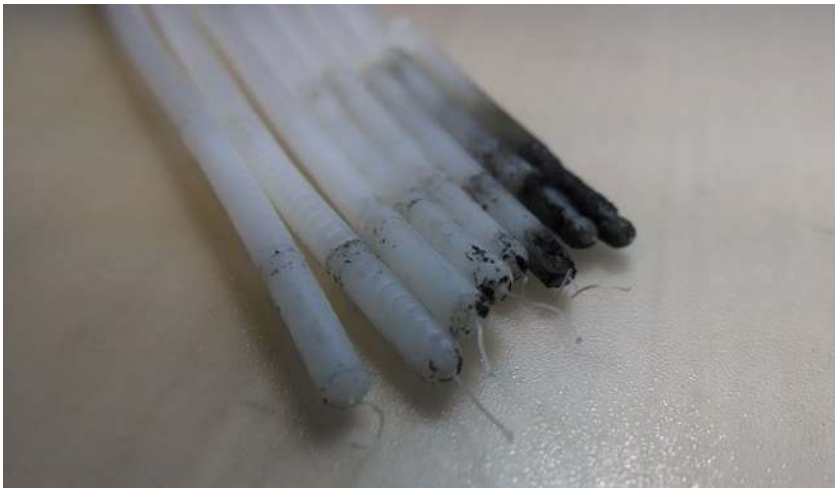


Figure 11-4. *Burned residue on cold-pulled filament*

Figure 11-5. *Nylon with residue of overheated plastic*

■ **Tip** You might want to do cold pulls from time to time as a preventative measure if your print quality seems to be degrading.

www.it-ebooks.info

Wire Brush Bristle

Usually a cold pull will clean a nozzle. However, if not, there is probably a hard bit of debris in your nozzle. One way to poke out a hard clog is to take a bristle from a wire brush and push it into the nozzle. The bristle typically does not clear the nozzle. It only dislodges the clog so that hot plastic can flow past it and then harden around it so that it can be pulled out. Occasionally, this will also break up the clog enough to allow it to be pushed out of the nozzle in smaller pieces.

Figures 11-6 and 11-7 show this process. Pull a bristle out of the brush with a pair of pliers and poke it into the nozzle. Then try a cold pull to see if you can pull the debris out. Note that the nozzle has to be hot for this maneuver to work, because otherwise the nozzle will be clogged with solid plastic. Be careful not to get your fingers near the hot nozzle.

Figure 11-6. *Extracting a single bristle from a wire brush*

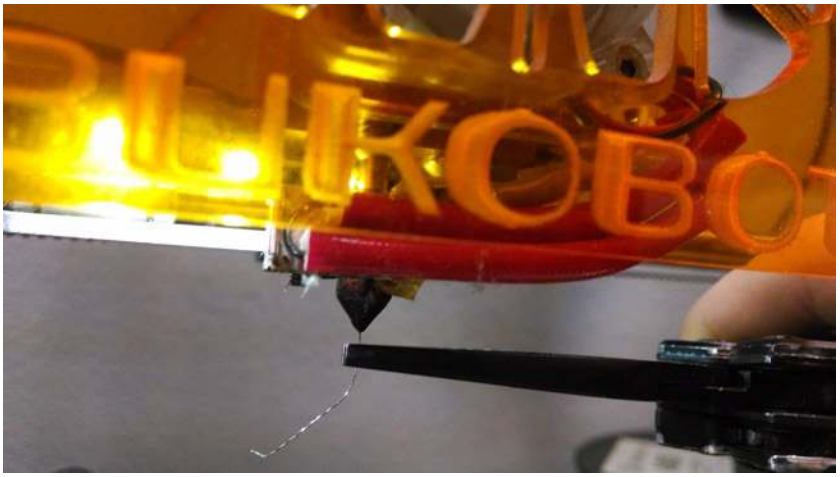


Figure 11-7. *Using the wire brush bristle to clear out the nozzle*

www.it-ebooks.info

Extruder Drive Gear Teeth Clogged

If you have been trying to extrude filament into a clogged nozzle, the drive gear may have been digging into the filament and clogging up the gears with ground-up filament. Check this too if you had to clear the nozzle. Otherwise, filament may not feed well, and you might think that the nozzle is still clogged. Pick and/or blow it off carefully and be sure you are not blowing plastic dust someplace where it will cause other problems.

Eliminate Stringing

Sometimes a print will come off the machine with strings everywhere. Often this means that the retraction settings (under Printer settings in the slicing programs—see Chapter 5) are not correct. When a printer is extruding and has open spaces in a layer, printers pull the filament back so that stringing does not occur. For a Bowden extruder (a tube between the drive gear and the nozzle), 2 mm or so is enough, although with long Bowden tubes you may need to pull back as much as 10 mm. For direct-drive extruders (where the gear is right by the nozzle), generally 2 mm or less is more appropriate. If you have problems with stringing, you may want to increase the retraction length slightly. Figure 11-8 shows what it looks like if retraction is turned off completely versus being set correctly for a particular printer.

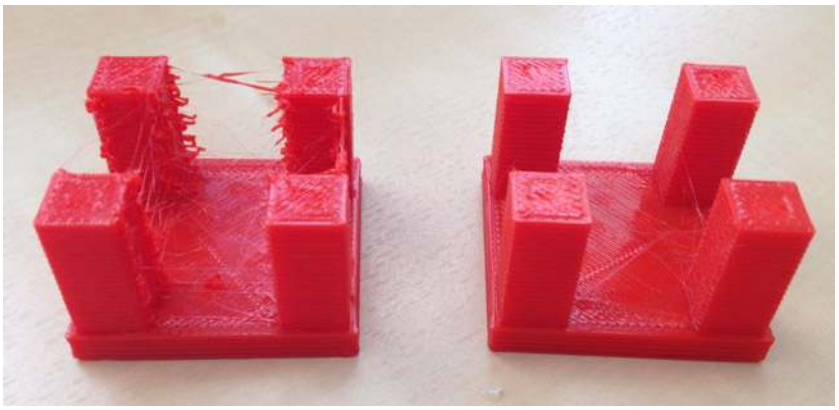


Figure 11-8. *A miniature table printed (upside-down) with retraction disabled (left) and set correctly (right)*

Software Upgrades

If you are using an open-source printer, be cautious about upgrading to a new version of any of the software packages as soon as they are released. Sometimes it is best to wait a bit and read the user reviews. Many of these programs have a terrific volunteer base (or a small paid staff), but their ability to test on all platforms usually is not exhaustive. If you are in the middle of a critical set of prints, wait to upgrade until having problems with the new software would not be disastrous.

www.it-ebooks.info

■ **Tip** If you start changing slicing settings, be sure to write down what you changed and just change one setting at a time to see the result. Otherwise, reconstructing what does and does not work can be very hard.

Summary

This chapter covered some common symptoms of trouble during the 3D-printing process and ways to resolve, and in some cases prevent, these problems. This chapter reinforced some of the suggested best procedures described in Chapters 5 through 8 and left you with a bit more understanding of the 3D printer as an interacting hardware and software system.

www.it-ebooks.info

PART 4

Using Your Printer

This last part looks at how you might use 3D printing in several settings. First, Chapter 12 discusses how some early adopters are using 3D printing to teach design and bring history to life in museums and classrooom settings. It also looks at how 3D printing can particularly help the visually impaired and other special-needs students.

Chapter 13 covers how molecular biologists in particular are creating physical models to help them think about and design complex biological and chemical structures. This chapter also talks about how to use 3D printing to teach math concepts.

Finally, Chapter 14 takes the risky step of looking into the future of 3D printing to see how the field may grow and evolve in the coming years in terms of technology and business trends and the needs of users all over the world.

www.it-ebooks.info

CHAPTER 12

Printers in the Classroom

People love to watch 3D printers in operation, and there is something magical about seeing a print materialize from nothing. In this chapter we discuss how to use 3D printers to motivate students to learn design skills, STEM (science, technology, engineering, and math) subjects, art, and history. 3D printing can also be valuable as a tool to help students visualize abstract concepts or a piece of history, like the boat design we will see later in the chapter.

This chapter provides some ideas about using a 3D printer in classrooms, as well as informal learning environments such as museums and after-school programs. Visualizing science and math is critical in the classroom too; both are discussed separately in Chapter 13.

Teaching Design, Engineering, and Art

One of the best things to teach with 3D printing is the process of design itself. It is not easy to learn to define a problem, analyze all the factors that go into a good solution, and then implement that solution in the real world. Having a 3D printer available can make for a much more realistic experience than just building something in a computer aided design (CAD) program alone. The following example illustrates how 3D printing can aid in the development of a design solution.

The Windward School on the west side of Los Angeles had a problem: their drain covers (Figure 12-1) were continually being broken by the groundskeeping equipment.

Figure 12-1. *The drain cover problem to be solved. Photo courtesy of The Windward School*

www.it-ebooks.info

Windward's Science Department Chair Simon Huss decided that designing a better drain cover would be a great exercise for his 12th-grade Principles of Engineering class. He set them the task of designing a drain cover that would not be damaged by the lawn equipment. He was intrigued to watch the students start out more or less duplicating the (unsuccessful) original design and then go progressively farther away from it.

Figure 12-2 shows the progression of the students' designs, with the original design (as in Figure 12-1) in the lower left, and the students' subsequent redesigns progressing from left to right. The designs progressively got flatter and simpler until the students wound up with the flat, showerhead-like drain on the lower right. That design worked better and was easier to 3D print than the ones that were more similar to the original. The students learned all the practical issues inherent in solving a real problem. A real problem required learning 3D printing at a more sophisticated level than an abstract exercise.

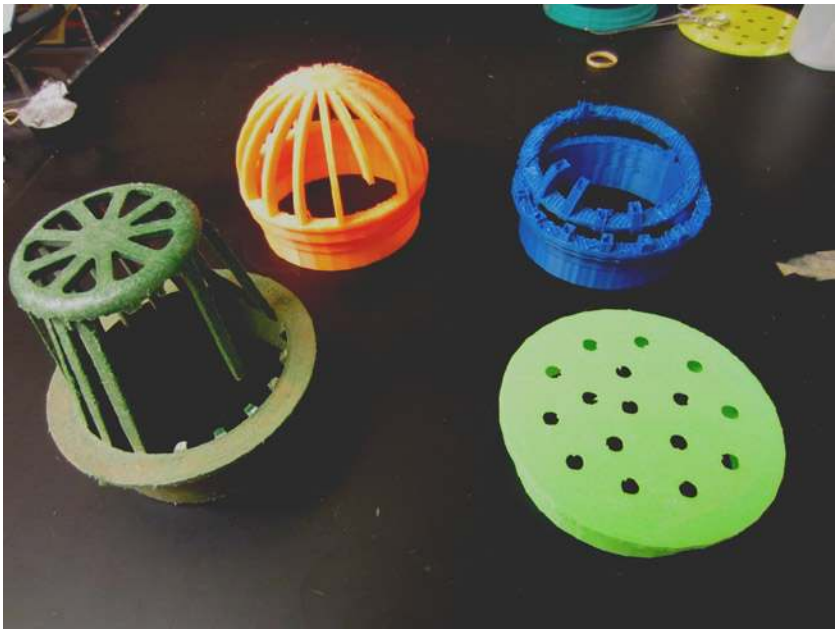


Figure 12-2. *Evolution of the solutions, developed in clockwise order from lower left. Photo courtesy of The Windward School*

Design can be taught more simply, however. The stereotypical thing to do in a first 3D print is a keychain fob with initials or graphics on it (like the one shown printing in Figure 12-3). Though a seemingly trivial exercise, even this small creation requires an understanding of many of the tradeoffs covered in Chapter 4, such as considering how to orient the piece to the build platform and how to deal with overhangs. It also avoids the issues that arise when beginners download a complicated model and try to print it. Starting with a simple design and working up from there is better.

www.it-ebooks.info

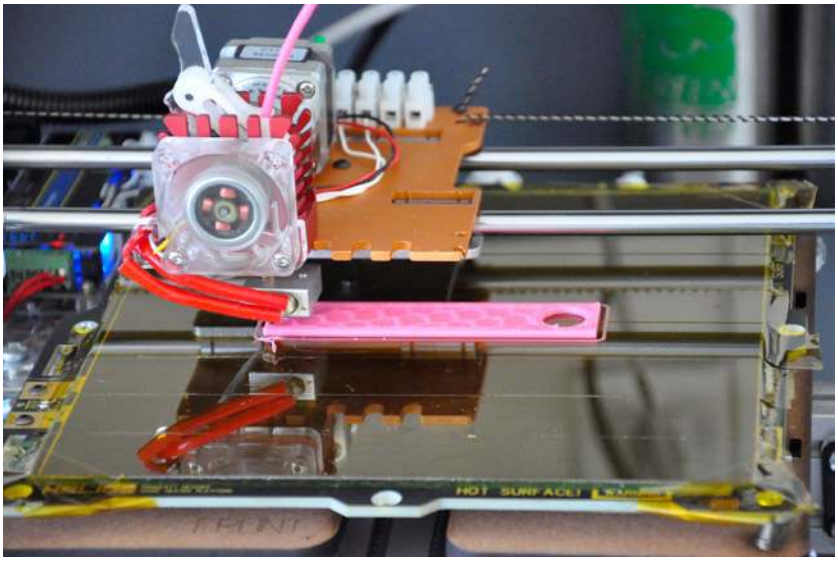


Figure 12-3. *Printing keychains—you can start simply. Photo courtesy of Windward School*

Tinkercad (Chapter 4) is a good program to use for beginning designers. Regina Rubio, a teacher at Windward, says that she had 8th-grade students start with objects from online databases. The students imported the downloaded designs into Tinkercad and then modified them. Such a process builds confidence and lets everyone at least build *something.*

She discovered that some natural team-building occurred as the students learned to use the printers. Some students learned right away and started helping others. Students brought their friends in to see what they were doing in the class, which created some word of mouth. "There was a genuine curiosity," she said, among students.

Those in engineering and design classes have a leg up on using a 3D printer because the students frequently have been taught a 3D CAD program (or are taught the programs in parallel with learning how to 3D print, and are motivated by solving a problem). 3D printers can be a boon for fine artists as well, as a new medium that allows incremental experimentation and prototyping.

However, some fine art teachers who come from a traditional sculpture, painting, metalworking, jewelry, or ceramics background may initially find the electronics and software aspects of 3D printing intimidating, or may have unrealistic expectations about what a consumer-level printer can do.

If you are a teacher with limited computer and electronics experience, find yourself a colleague and team up. 3D printing is a very natural, interdisciplinary icebreaker. Your friend who teaches CAD might not be very good at the manual aspects of cleaning up a print and can learn the finishing techniques described in Chapters 9 and 10 from you, while you learn the techniques in Chapters 4, 5, and 6 from them.

■ **Note** Fine artists sometimes are dismissive of consumer-level printing because of the layer lines and resolution limitations. This is particularly true (as we saw in Chapter 11) for PLA prints, which cannot be smoothed easily. If you are a sculptor developing a class incorporating 3D printing for the first time, consider that, like brush strokes on an oil painting, layer lines are inherent in a filament-based medium. On the other hand, complexity and iterating a design are easier to deal with in 3D printing than in traditional sculpting.

---

www.it-ebooks.info

If you are a school's computer networking person and you suddenly find yourself in charge of some hardware and chemicals that look like shop class, you may need to seek out an art teacher or other colleague for those practicalities. This can be particularly awkward if your school no longer has a shop class or full-time art teacher. Sometimes schools put the librarian in charge of 3D printing resources or even a full hackerspace (typically, a room with soldering irons and 3D printers). If this is your situation, do not panic—add to your team, as noted in the following Tip.

If you are a school administrator looking at buying 3D printers, consider the need for some cross-training and cross-fertilization for your staff to make your 3D printer purchase as productive as possible. Allow some time for a bit of a learning curve on everyone's part.

■ **Tip** If the resources at your school do not really cover the needed skillsets for 3D printing, look to a local hackerspace or community college for some professional development to learn the crossover skills. If there are no local resources, consider contacting the closest group at `http://hackerspaces.org/wiki/List_of_Hacker_Spaces`. As discussed in Chapter 3, the open source community believes strongly in aiding new users, and you will find people who are happy to help, even if remotely.

Hands-on History

3D printing allows for far more robust visualization of objects from the past than might be possible any other way. Museums have always displayed pieces of history. What if a whole class or group of visitors to a gallery could look at and play with plastic replicas of museum artifacts that otherwise perhaps might exist only as historic drawings? This section describes collaboration with a museum, but the process described here could just as easily be undertaken by students, perhaps based on less-rarified material.

The author of this book received permission from the MIT Museum's Hart Nautical Collection to take some historic drawings and work with her colleagues to create a William Hand, Jr. boat and a cleat by Nathanael Green Herreshoff. These creations were displayed (and printed while visitors watched) at the Museum during the 2014 Cambridge Science Festival.

William Hand, Jr. Boat Hull

William Hand, Jr. (1875–1946) was a nautical engineer. He started out designing yachts, but soon became known for developing a characteristically shaped V-bottom that was used on power boats, schooners, and motorsailers. Many of his plans are now in the Hart Nautical Collections at the MIT Museum. Figures 12-4 and 12-5 are two views of a classic William Hand, Jr. boat from that collection.

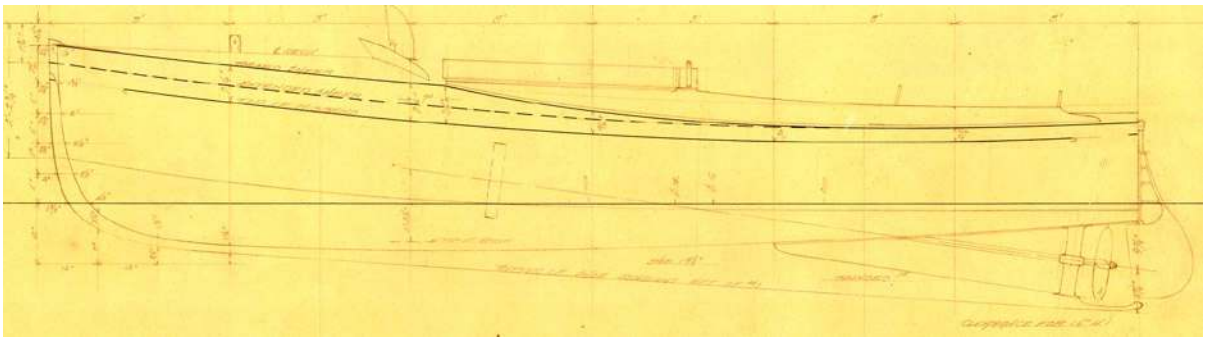


Figure 12-4. *Side view of William Hand, Jr. boat. Courtesy of the Hart Nautical Collections of the MIT Museum*

www.it-ebooks.info

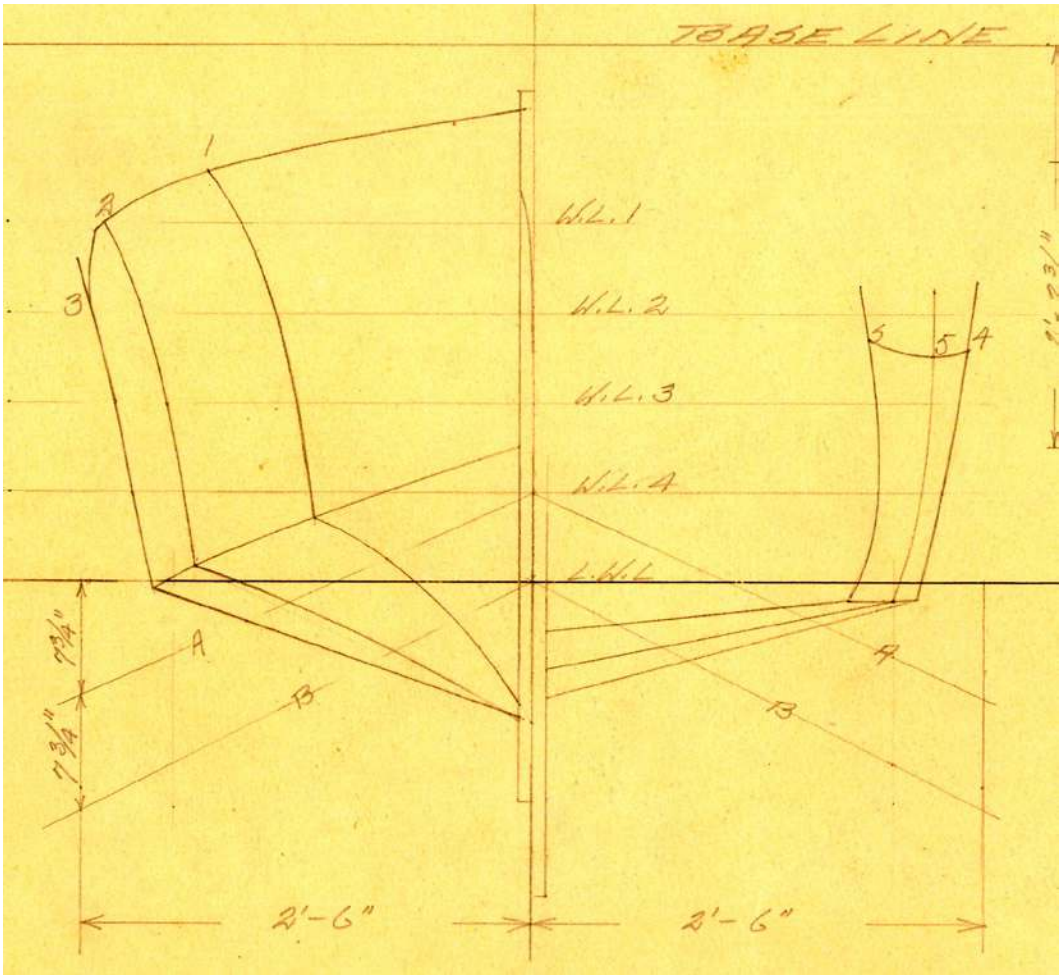


Figure 12-5. *Front view of William Hand boat. Courtesy of the Hart Nautical Collections of the MIT Museum*

■ **Tip** To see how these boats evolved, see www.handdavisyachtdesigns.org or the *Hand-Davis Collection Catalog*, available by contacting the Hart Nautical collections curator at http://web.mit.edu/museum/collections/nautical.html.

Diego Porqueras, the founder of Deezmaker 3D Printers in Pasadena, California, took on the challenge of recreating the ship based on these plans. He brought the plans (provided in scanned, electronic form) into Solidworks and used a combination of tracing over the drawings and using the provided dimensions to create the hull.

It became apparent, though, that the dimensions did not quite match up. It turned out (after talking to the curator and a modern shipbuilder) that plans from that era assumed that a master shipbuilder would be the one using the drawings. You were just supposed to know where to add some material as needed or to make allowances—rather quite different from the current era of computer-controlled manufacturing or 3D printing.

www.it-ebooks.info

After a bit of detective work, Porqueras was able to create a printable STL file for the boat. Figure 12-6 shows it in half hull form. This half hull was also cast in aluminum, as illustrated in Chapter 9. Half hulls are typically carved out of wood and mounted. Because a half hull has a flat back, it is nearly ideal for 3D printing. The only thing that was difficult about the actual 3D print, once the STL file existed, was the delicate propeller area at the lower right of Figure 12-6.

Figure 12-6. *3D-printed half hull of William Hand, Jr. boat. Created by Diego Porqueras from original design plans with permission from the Hart Nautical Collections of the MIT Museum. PLA print, hand-sanded*

■ **Note** The process of developing a "to be 3D printed" model is different from creating plans for a person to use. Sometimes designers develop models that are aggregated from different subassemblies, which then have models of multiple parts occupying the same (virtual) space when they are aggregated. The Sketchup program is particularly notorious for this, and the result is non-manifold models that may slice unpredictably.

We also printed full-hull models, as shown in Figure 12-7, to give an idea of the overall hull's appearance. After some experimentation, we decided that printing them tail-down worked best. We also printed out six at a time so that we could leave the museum some hands-on pieces for their education programs.

www.it-ebooks.info

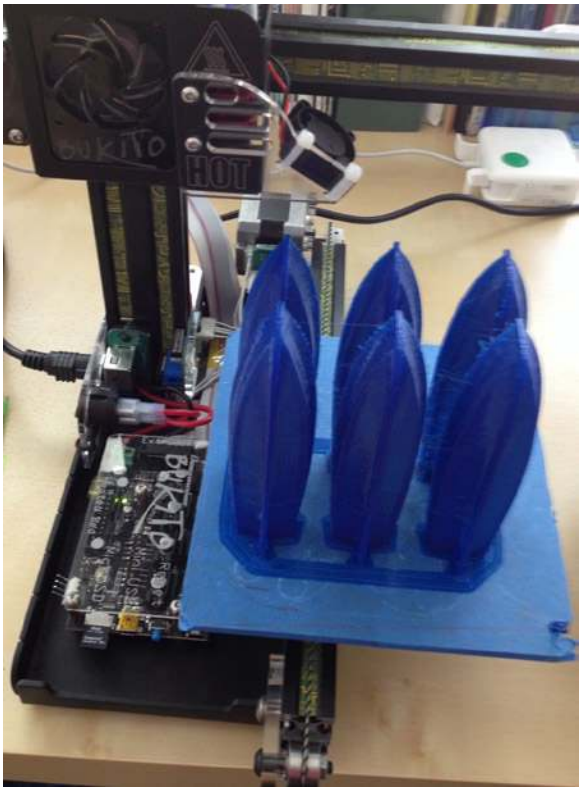


Figure 12-7. *Printing copies of the William Hand, Jr. boat hull. Created by Diego Porqueras from original design plans, with permission from the Hart Nautical Collections of the MIT Museum. PLA prints*

These full-hull prints were challenging, since we wanted to avoid using support (because of the delicate propeller area) but there was not a lot of contact area on the base. In the end we used a wide skirt and brims around each piece, which created enough stability that the prints would survive to completion without the prints being knocked off the print bed when subsequent layers were printed.

Because each hull was relatively small, printing six at a time actually took less time than six times printing one at a time would have. Because each layer needs to cool before the next one is printing on it, a tall, skinny object's fastest print time can be limited by the minimum layer time. Printing several at once can collectively take up the minimum layer time, whereas printing one at a time would require a bit of a wait each layer, or at least for some of the layers.

Herreshoff Cleat

Nathanael Greene Herreshoff (1848–1938) was one of MIT's earliest graduates as a member of the class of 1870. With his brother John Brown Herreshoff (a blind boat builder), he founded the Herreshoff Manufacturing Company. The company became known for boats that were both fast and elegant. Between 1893 and 1914, Nathanael Herreshoff designed and the company built five America's Cup winners.

The Herreshoffs developed many innovations that are still used in modern yachting. One notable invention was the Herreshoff cleat, a hollow but strong design for securing rope. If you search "Herreshoff cleat" online, you will see many different variations available for sale.

www.it-ebooks.info

The Hart Nautical Collections of the MIT Museum also gave permission to the author of this book to use plans in their collection for a Herreshoff cleat. As with the boat in the preceding section, Diego Porqueras used Solidworks to recreate the design. In this case, though, the drawings represented all the required dimensions, as modern ones would have. Figure 12-8 is a rendering of this model.

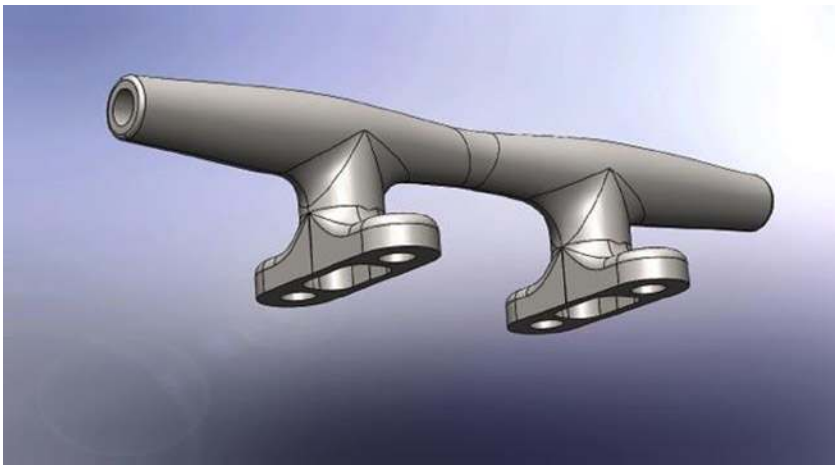


Figure 12-8. *Herreshoff cleat, created from original design plans with permission from the Hart Nautical Collections of the MIT Museum. Solidworks rendering by Diego Porqueras*

Creating the 3D-printed model, however, was challenging. The cleat is hollow, and there is no way to print it without support. Support inside the barrel of the cleat would be pretty much impossible to clean out. After some consultation with Deezmaker's Rich Cameron, we used the slicing program Cura (mentioned briefly in the "Alternative Hosting and Slicing Programs" section at the end of Chapter 5) because it has a feature that allows the user to create support only where the support would touch the platform, skipping support that would be inside hollow spaces of the model.

The hollow-but-rounded horizontal arm of the cleat had a gentle enough slope from layer to layer that the printer was able to bridge across that open internal space without support. Figure 12-9 shows one of the many experiments while printing the cleat. Figure 12-10 is the final version (with supports removed) that we printed for visitors at the museum event.

www.it-ebooks.info

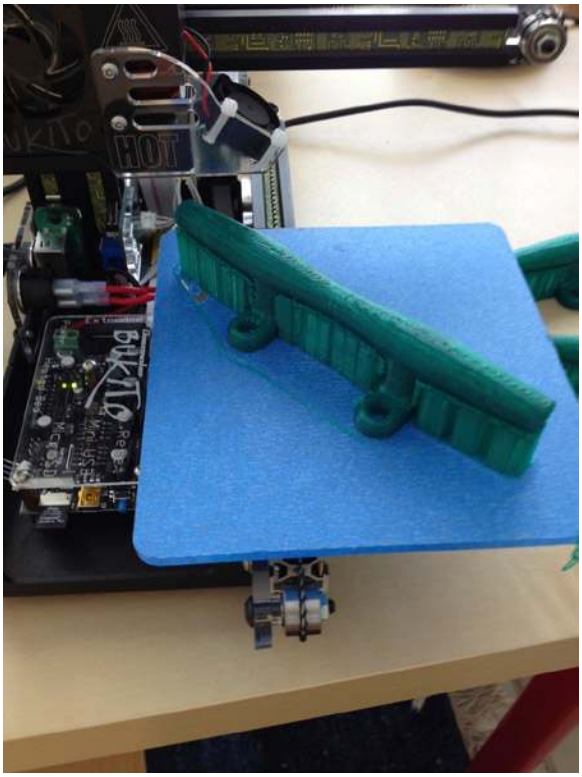


Figure 12-9. *Herreshoff cleat 3D-printing experiment. Model created by Diego Porqueras and the Deezmaker team from original design plans, with permission from the Hart Nautical Collections of the MIT Museum. PLA print*

Figure 12-10. *Herreshoff cleat 3D print with support removed. Created by Diego Porqueras and the Deezmaker team from original design plans, with permission from the Hart Nautical Collections of the MIT Museum. PLA print*

www.it-ebooks.info

■ **Note** For more about Herreshoff, see the MIT Museum's page at http://herreshoff-legacy.mit.edu and the Herreshoff Marine Museum's web site at herreshoff.org.

Reactions to the 3D Prints

We exhibited 3D-printed boats and cleats, and 3D printers actively making them, at the MIT Museum during the April 2014 Cambridge Science Festival (http://cambridgesciencefestival.org). Figure 12-11 is a picture of the display at the museum—we were continuously surrounded by visitors, many of whom knew quite a bit about the history and designs but were intrigued to actually see them and be able to handle them.

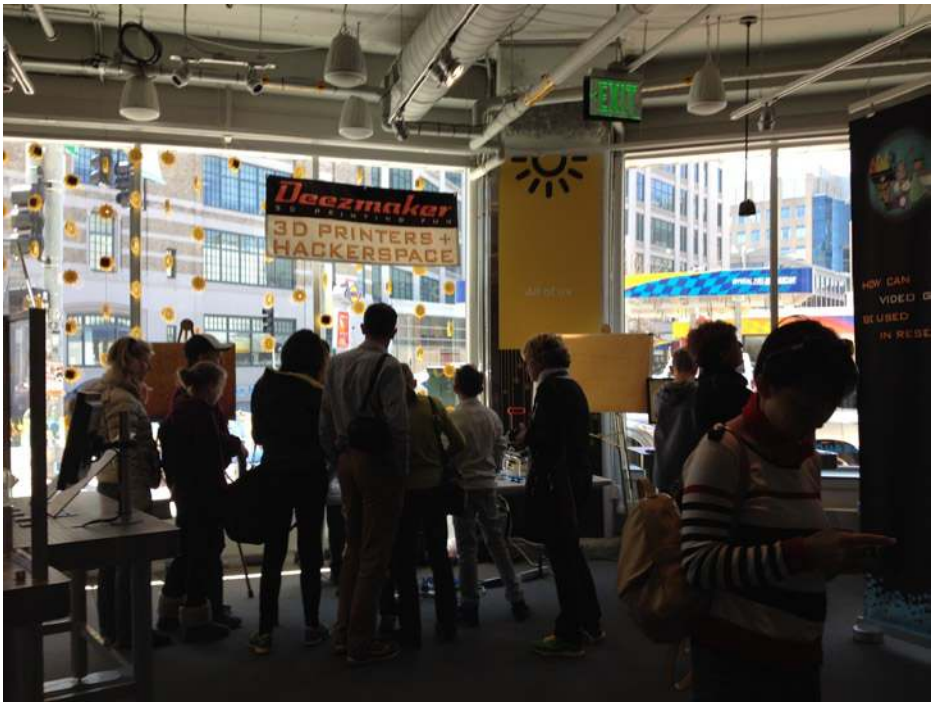


Figure 12-11. *3D printing exhibit at the MIT Museum during 2014 Cambridge Science Festival*

The full-hull models (the ones in Figure 12-7) were just a few inches long and looked a little too much like toy boats, so they kept finding their way into a marine biology aquarium across the exhibit hall courtesy of young admirers. Fortunately, the sea life did not seem to mind the small William Hand PLA boats bobbing on the surface, but we did make mental notes to consider what else might be around us in a museum environment in the future.

The museum created a large-format image of the drawings on easels on either side of the display table, as shown in Figure 12-11. Visitors could pick up the 3D-printed objects and think about the process of translating a drawing into reality and how many design decisions needed to be made along the way, both for the original boat and cleat and their 3D-printed replicas. We were actively printing the cleat and boats, which also was of intense interest for visitors who had not seen a 3D printer in person before.

www.it-ebooks.info

The event was just a one-day exhibit, along with other nautical-themed activities and displays. The museum staff told us later on that had been one of the best-attended days of the year. Our prints could not take credit for all of that, of course, but we like to think we helped generate some good energy and curiosity about the design process and the historic items themselves.

After that event, we took the same display to Cape Cod Maker Faire. Because of the location (in Barnstable, Massachusetts), there were many people who both knew what a Hand speedboat looked like and recognized Herreshoff's style. We found the historic prints good conversation starters for people who otherwise might have dismissed 3D printing as something they could not understand.

Learning Through Re-Creating History

We learned a lot from our exercise in historic re-creation and also realized how valuable this exercise would be for students learning history, design, 3D CAD, and a variety of other subjects. This section lists some challenges and opportunities to keep in mind if you want to try a similar exercise with your own students or visitors.

Challenges

Recreating historic designs is challenging for several reasons:

- Even if plans for the historic design appear to be very detailed and complete, they may be intended as communication from master craftsman to master craftsman and therefore leave out a lot. Ferreting out what might be missing is an opportunity to in part re-create the process at the time, but expert historical advice or a lot of side research may be required.
- Unless the historic object is simple, sophisticated CAD skills are needed to go from a set of 2D plans to a 3D model. A project like this might be good as a "master class" for CAD students.
- The models that are created may be difficult to 3D print. Something that is easy to make in wood might not be so simple to recreate at a smaller (or larger) scale with 3D print technology. Creative decisions about how much detail to keep and how much to ignore will be needed, based on what features are of interest.
- The end-to-end process is time-consuming.

Opportunities

Re-creating historical designs in physical (versus virtual or 2D) form has several beneficial effects:

- The process requires learning about the fabrication methods and design process of the time, rather than just the result. As such, it might be interesting as a way to get students to think deeply about the design process itself, rather than design as a means to an end product.
- If the part is functional and a plastic print will be strong enough to emulate the original use, it can be incorporated into functional demonstrations as well. If students are too young to do any, or most, of this process themselves, it might be interesting to develop some demonstration or hands-on interaction pieces for classroom use.
- An exercise like the cleat or boat development described here might be a good senior undergraduate semester or summer project, or perhaps an interdisciplinary capstone team project between history and engineering majors.
- If you work for a museum, creating a 3D design of an artifact and then printing it may be a good process to get a few dozen of some items in your collection to use for public programs that would be prohibitively expensive to create any other way.

www.it-ebooks.info

- In a somewhat different sphere, archeologists and paleontologists have been interested in finding ways to scan bone fragments or other objects they find to more easily share pieces of objects with colleagues and to play around with pieces that are not fragile and irreplaceable. Similar sharing of objects from a museum collection with other institutions might be possible.

The bottom line is: choose your project carefully, be sure you have the resources to pull it off, and get ready for you and your students to have a very unique interaction with history!

The Special-Needs Student

3D printers can be a real boon for students who are tactile learners—those who learn primarily by touching objects and using them. Visually impaired or blind students are very dependent upon having objects that they can touch to learn abstract concepts such as math and science. Chapter 13 talks about visualizing math and science in general, but here we want to note the promise of 3D printing for teaching the visually impaired.

Lore Schindler is a teacher and technology coordinator for the visually impaired in the Los Angeles Unified School District. She is also on the DIAGRAM (Digital Image And Graphic Resources for Accessible Materials, http://diagramcenter.org) committee, a group developing standards and tools for digital media to assist students who have disabilities that make using print materials difficult. Along with her colleague, high-school teacher Michael Cheverie, she has been considering how to employ 3D printing to assist her constituents.

The need for tactile aids becomes greater as students reach high school because it is easier to find objects to illustrate concepts found in curricula for younger children. Once one gets into chemical structures and mathematics at the precalculus level, illustrating with found objects becomes more difficult.

As of this writing, Schindler, Cheverie, and Deezmaker 3D printing are just beginning to mentor Career and Technical Education students at Pasadena City College (PCC) who have solid backgrounds in 3D CAD modeling. The PCC students will explore whether it will be possible to create models to teach visually impaired high school students some key chemistry concepts. As a bonus, the PCC students will have to review and think deeply about the high-school chemistry that they are going to "explain" in a 3D model. If you are interested in this topic and want to see the various early-stage efforts, search the web for "3D print visually impaired" or similar phrases.

Other groups have been interested in low-cost, crowd-developed prosthetic limbs (hands, in particular) for those who could not otherwise afford them, such as victims of violence in third-world countries. Thingiverse (www.thingiverse.com, discussed in Chapter 4) has many examples of prosthetic hands. 3D-printed prosthetics raise some interesting issues about where the line between compassionate hobbyists and medical practice should lie. See Chapter 14's discussion of the future of open source medical applications for some more ideas about these issues.

After-School Activities

3D printing can support a variety of after-school and informal learning activities. Earlier in this chapter we discussed a museum interaction; in this section, we will talk more about ways that students in after-school activities might benefit from 3D printing. 3D printing can be a creative endeavor to build confidence and can be a very practical tool to solve problems.

Robotics Clubs and Teams

Robotics hobbyists and teams can use 3D printing if they are participating in events where the rules allow students to 3D print parts. The process of learning how to design and print a part can also start a discussion about how to decide whether or not a part will be strong enough, whether the current design is adequate, and even when to stop designing and iterating and declare the machine finished. Robotics clubs that are already using a lot of the relevant CAD software can be a nucleus for 3D printing expertise if a school does not have a natural alternative.

www.it-ebooks.info

DIY Girls

One organization successfully using 3D printing as part of an overall program of learning-by-making is DIY Girls (www.diygirls.org). DIY Girls is a project currently based at a school in the city of Pacoima, a low-income community in the San Fernando Valley, the northern portion of Los Angeles County. The first school in the DIY Girls program had a student body that was 99% Latino, with 89% of students qualifying for the U.S. federal free or reduced-cost lunch program.

The program starts with 5th-grade girls and puts them on a track to technical careers by teaching them hands-on skills that would not traditionally be available to them, including soldering, 3D printing, programming, and building electronics. In Figure 12-12, the girls are working with their printer. The intent is to make girls confident and to themselves as able to take part in STEM careers. The program overall covers 5th through 8th grades, with training also available for adult women in the community who want to learn technological skills. The founder is Luz Rivas, an MIT alumna who as a child went to the school where she now has started this program.

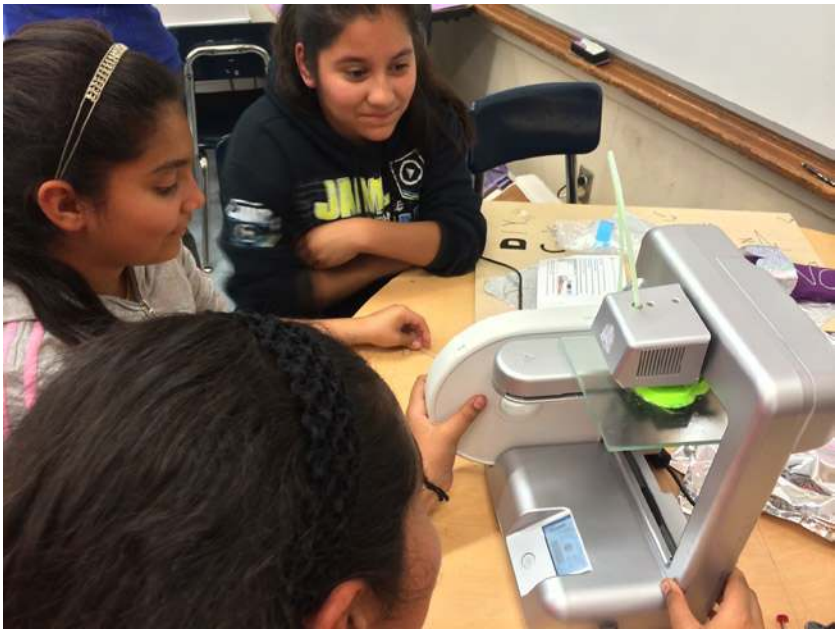


Figure 12-12. *DIY Girls learn 3D printing by making toys. Photo courtesy of DIY Girls/Luz Rivas*

Young Maker Programs

There are teen-oriented maker programs popping up as well. In summer 2014, Make Media (who put on Maker Faires and publish *Make* magazine) held a virtual camp, using the Google+ platform. More information about Make Media's youth programs generally can be found at http://youngmakers.org.

Career Tech Ed

Learning how to use a 3D printer for its own sake is a useful skill, as more industries start to experiment with it, at least for prototyping. Since G-code (Chapter 6) is also used for many CNC (computer numerically controlled) machines, 3D printing can also be a gateway to more complex machine tools, although the code itself is very different for these

www.it-ebooks.info

tools than for a 3D printer. Because many high schools no longer offer shop class due to a perceived lack of interest, liability concerns, or other factors, learning 3D printing may be one of the few ways of imparting at least some concept of how to use industrial machinery other than learning on the job.

Community colleges often have a program called Career Tech or something similar which is aimed at a two-year degree or perhaps a certificate program. If you are looking to make a career switch, you might see whether your local community college degree program or extension program offers some courses of interest in 3D printing and other "making" skills.

Early-Adopter Experiences

There are some common experiences that all educators face as they start to use 3D printing in a classroom or an informal learning environment. The first one is that any 3D print takes a while. This means that if you have a one-hour class with 20 students, you are pretty much out of luck when it comes to printing something from everyone with any reasonable frequency. There are ways around this:

- Have group design projects (some sort of competitive team project, for example).
- Do some simulated prints away from the printer (walk through the G-code visualization in Repetier Host, for example, to check for obvious errors before trying to print).
- Find projects in which each student print can be physically small and fast to print.
- And, of course, find a way to buy more 3D printers.

3D-printer projects should be undertaken with age-appropriate expectations and supervision, as with any mechanical tools. Particularly prior to the high school level, the actual printer operation will need to be done by a teacher or technician for the safety of both the students and the printer.

An informal, anecdotal survey of some educators actively using 3D printing revealed some common observations. The one mentioned most frequently is that it is important for the teacher to be very comfortable with the machine and to learn as much as possible about it. The learning curve is still long, and teachers never have enough time to learn any new tools as thoroughly as they would like.

The reality of open source printing in particular is that you have to be happy with tweaking the printer a bit, and if you are too squeamish about doing that, your ability to print will probably be limited. Students have an uncanny ability to come up with things that are difficult to print, and a bit of willingness to fail as a collective learning experience is an important trait for anyone teaching a class that incorporates 3D printing.

3D printing is complex, and, as we saw in Chapters 5 and 6, there are a lot of settings to play with. If you are teaching in a new class incorporating 3D printing and you are only comfortable with a subset of your printer's capabilities, just stay in that box for a little while and then walk out to more complex things little by little.

If you are an expert training someone else, resist the temptation to dump details about every possible setting on your hapless colleague in one sitting. We have had success with handing out "cheat sheets" (more or less the information in Appendix A) and highlighting just a few settings. Over time, people can learn the rest on their own.

Summary

In this chapter we reviewed some case studies and drew some conclusions about the usefulness of 3D printing in classrooms, museums, and after-school activities. 3D printing is a natural component of teaching prototyping and design skills, and also for learning how these skills were practiced in the past. We reviewed some of the challenges inherent in the current state of the art (long print times and learning curves) and some constituencies who can uniquely benefit (like the visually impaired and students who would like to make a living as machinists).

This chapter primarily focused on the engineering, technology, and art-learning opportunities; Chapter 13 focuses on broad issues of using 3D printing for the more abstract visualizations needed by students and professionals in mathematics and the sciences.

www.it-ebooks.info

CHAPTER 13

Scientific Visualization

Scientists, engineers, and mathematicians have always used available computer graphics to visualize models of physical systems as well as of abstract concepts. Although computer models on a 2D screen can enable a user to see things that otherwise might not be readily visible, sometimes there is just more intuition to be had with a physical model that can be touched and manipulated. In this chapter we will talk about some early adopters who are using 3D printing to visualize scientific and mathematical concepts.

Chapter 12 talked about using printers in a classroom generally; this chapter covers 3D models intended to help students (or professional researchers) visualize mathematical or scientific concepts. Mathematics "manipulatives" have a long history in the classroom. 3D printing allows development and replication of custom manipulatives by each teacher and custom models by each researcher. As a bonus, the STL files can be used across the hall or the continent.

Visualizing Molecular Biology

Molecular biologists have to think about the interactions of very complex molecules. Often they want to predict how several molecules will interact. There are big databases of the structures of scientifically-interesting molecules, along with references to journal articles about them. One very large database is the Research Collaboratory for Structural Bioinformatics (RCSB) Protein Databank (PDB) (www.rcsb.org/pdb), which is the United States' depository of a larger worldwide databank, the Worldwide PDB (www.wwpdb.org). These databanks are public resources for scientists to share information about the structure and function of proteins and other biological molecules. Now individual scientists who want to have a 3D model of a complicated molecule can 3D print one based on the information in these databanks.

Tip If you want to start printing molecules yourself, the PDB has a page of links to different molecular-visualization software. The links can be found on the RCSB site at www.rcsb.org/pdb/101/static101.do?p=software/software_links/molecular_graphics.html.

Some of the molecular biology visualization packages linked as noted in the preceding Tip are capable of taking in a PDB identifier and putting out an STL file for printing. Chimera (www.cgl.ucsf.edu/chimera/) has this capability, and other programs may be able to output a file that can subsequently be translated by other programs into STL. Depending on what you are doing with it (commercial versus educational use, for example), you might need to talk to the developing organizations about a license.

www.it-ebooks.info

Model Accuracy Considerations

If you are a scientist trying to figure out whether you can make a conversion to STL from your favorite software, try searching online on the file type your specialized software creates and add "convert STL" to the search query (that is, search on *XYZ file convert STL*.) That tactic will often drop you into some discussion forum where you can at least find other people trying to solve the same problem.

Once you figure out how to get an STL file and print it, you have to decide whether to believe the output and perhaps ultimately publish a paper based on it. Be skeptical about the results until you have a chance to validate them (by looking at an on-screen visualization, for example). Building intuition and brainstorming with colleagues are good roles for these models.

Sometimes the STL files made by these programs are not watertight and/or not manifold (see Chapter 4). The files can also be very large with many triangles, requiring some simplification (see Chapter 10's section "Printing Computationally Complex Objects"). When you try to fix these issues with the programs discussed in Chapters 4 and 6, simplifications and automatic cleaning may change surface details. If those details are important, cross-check with more traditional analysis tools before claiming a fantastic new discovery.

Example: 3D-Printed Models of Six-Helix DNA Bundles

Matt Gethers, at William Goddard III's Materials and Process Simulation Center at the California Institute of Technology (Caltech), needed to visualize a complex structure made of bundles of DNA. Gethers is interested in a field that has come to be called *DNA origami*.

DNA origami does not involve folding paper. Instead, it uses the fact that DNA can organize and build other structures made out of DNA under the right conditions. Researchers use small strands of DNA to fold a long strand of DNA into arbitrary shapes. This folded strand can then be used as part of a DNA assembly that can in turn assemble more complex structures. There has been interest in using the capability to deliver drugs.

Figures 13-1 and 13-2 show two views of molecules made up of six double-helix strands of DNA. This six-helix bundle is an early version of a DNA nanostructure. (It's not technically the origami that Rothemund invented, as it doesn't use small strands to make a new shape.) Gethers constructed virtual models of the molecules designed by Mathieu et al (cited in the Note that follows), using a string of specialized biological software. Figures 13-1 and 13-2 are photos taken by the author, used with the permission of Gethers and Goddard. Gethers wanted to 3D print his model so that he could better understand the structure of this complex biological molecule. He and his colleagues have found that having the physical structure is a boon both for privately viewing the structure and also for helping with the group's insight during collaborative meetings.

Figure 13-1. *End-on view of six-helix bundle DNA model. PLA print. Model courtesy of Matt Gethers, Caltech*

www.it-ebooks.info

Figure 13-2. *Side view of six-helix bundle DNA model. PLA print. Model courtesy of Matt Gethers, Caltech*

■ **Note** If you are interested in DNA origami for its own sake, a good overview is in the August 2009 *Wired* magazine article by Michael Eisenstein, "Self-Assembling DNA Makes Super 3-D Nano Machines," available at www.wired.com/2009/08/nanodna/. Another introduction is Paul Rothemund's 2008 TED talk (www.ted.com/talks/paul_rothemund_details_dna_folding).

The six-helix bundle in particular is discussed in a 2005 *Nano Letters* article by Fredier Mathieu et.al, "Six-Helix Bundles Designed from DNA," with an abstract available at http://pubs.acs.org/doi/abs/10.1021/nl050084f.

As you can see in Figure 13-1 and 13-2, there is a lot of fine detail on these models. Printing them in white or silver plastic seems to give the best surface feature detail. To give you an idea of what it looked like in person, people often mistook it for a piece of bleached coral.

Once an STL was available out of the early part of that workflow, it had to be cleaned up and substantially reduced in size (as described in Chapter 11). For complex models like this, "bare Cura" (the Cura slicing program not wrapped in a separate host program) often performs best. Cura's option to generate support material only where that support would touch the platform was used so that there was some solid surface under the irregular base (it was printed such that the long axis of the molecule was the vertical direction), but without internal support, which was not really necessary and would have been a mess to remove.

Visualizing Mathematical Abstractions

Mathematicians have always visualized their constructs graphically. However, 3D printing allows (literally) another dimension. For the rest of this chapter, we will look at efforts to take abstract concepts into a 3D-printed representation. Whether these representations are "mathematics" or "science" depends on the application, and we will not particularly worry about the distinction here. We will first look at some "pure math" applications (parabolas and some surfaces of revolution) and then move into ways of generating some mathematical functions that have important physical implications and manifestations, like sinusoids, in 3D.

www.it-ebooks.info

Parabola Math Manipulative

The Mind Research Institute (MRI) in Irvine, California, is the developer of JiJi (ST) Math. ST stands for "spatio-temporal." JiJi Math is a mathematics game that allows children to learn mathematics without words (in a spatial-temporal way)—a boon in particular for dyslexic or other children who might process the symbolic math just fine, but have a problem learning it if words are involved.

Matthew Peterson, CEO of the Mind Research Institute, has been exploring using 3D-printed *manipulatives* (objects that students can handle) to teach math. The one we will discuss here is to help develop intuition about parabolas (see Figure 13-3 for the equation, and shape, of a basic parabola).

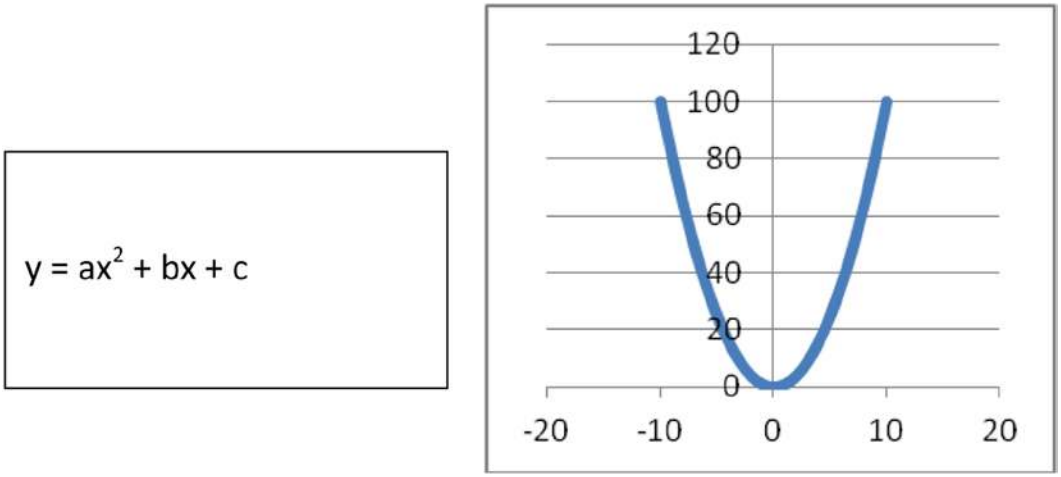


Figure 13-3. *Equation and graph for a parabola. In the graph, b = c = 0, a =1, and y is the vertical axis*

Students can have trouble understanding what changing the linear term (*bx*) actually does to the overall shape of the graph. Peterson developed the manipulative shown in Figures 13-4 and 13-5 to help them out. You can think of a parabola as the basic shape shown in Figure 13-3, plus an offset to move it up or down. The linear term adds a line to the base parabola. As the slope of that line shifts (moving the handle between the position in Figure 13-4 and the one in 13-5), the vertex of the parabola moves around.

www.it-ebooks.info

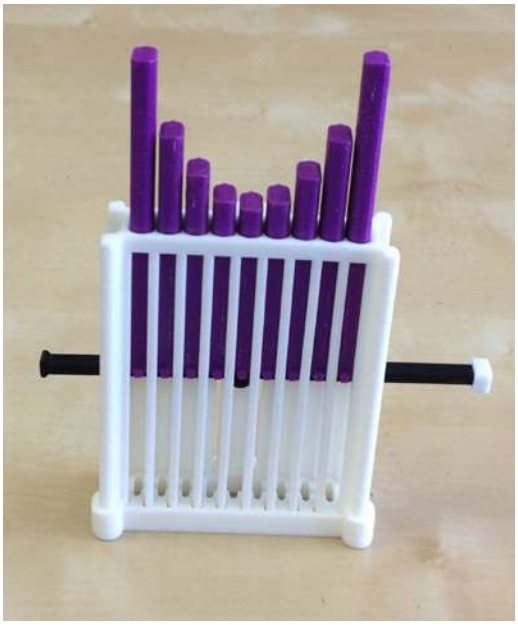


Figure 13-4. *Symmetrical parabola. Model courtesy of Mind Research Institute*

Figure 13-5. *The parabola with a positive slope (vertex moves negative, relative to Figure 13-4). Model courtesy of Mind Research Institute*

www.it-ebooks.info

The axis of symmetry of a parabola is given by the line $x = -b / (2a)$, where a and b are as shown in the equation in Figure 13-3. In Figure 13-5, we add a line with positive slope relative to the configuration in Figure 13-4, and the axis of symmetry moves more negatively, as we would expect.

■ **Tip** If you want to hear Matthew Peterson of Mind Research Institute talk about how to use this manipulative, you can watch him on this video: www.youtube.com/watch?v=PmrzcR4H6xw.

He describes his philosophy more broadly in a TEDx talk: www.youtube.com/watch?v=2VLje8QRrwg.

To download and try this manipulative (which is a pretty challenging print with tight tolerances), you can retrieve the parts at www.thingiverse.com/thing:186452. The print shown in Figures 13-4 and 13-5 was printed by Matthew Peterson, CEO of Mind Research Institute, in ABS.

Surfaces of Revolution

Surfaces of revolution are surfaces generated by taking a curve (technically, the *generatrix)* and rotating it around an axis. There are sophisticated mathematics and engineering programs (for example, Mathematica) that can generate a complex surface and then an STL for printing. But suppose you just have minimalist capabilities? This and the next section show you what you can do with just OpenSCAD.

OpenSCAD (Chapter 4) is a particularly good tool for generating 3D versions of surfaces of revolution to learn more advanced mathematics or perhaps to explore different shapes for an artistic or architectural endeavor. Figure 13-6 shows the code for and a rendering of a surface where the vertical dimension is proportional to the fourth power of the horizontal one.

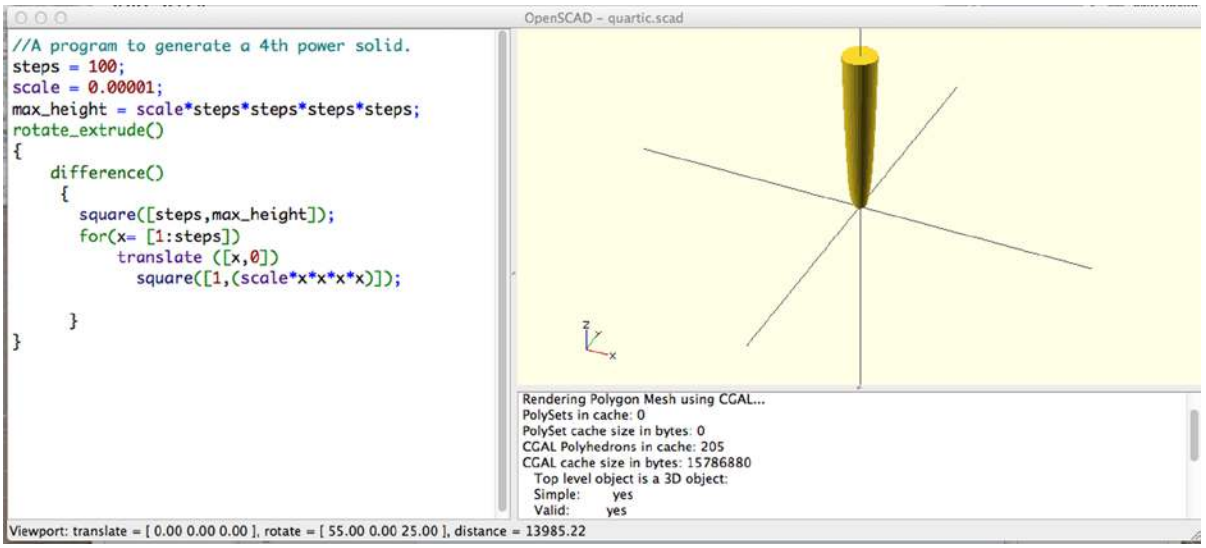


Figure 13-6. *OpenSCAD code to generate a fourth-power surface of revolution with rotate_extrude()*

www.it-ebooks.info

Because OpenSCAD does not have the ability to create a surface of revolution directly, we have to borrow a few techniques common in other scientific modeling, where we break up what we are trying to compute into smaller, easier-to-compute pieces. This task was comprised of the following steps:

- We created the two-dimensional graph of the fourth-power curve by making 1mm-wide strips along the *x* axis of height equal to the fourth-power function. This gave us the 2D outline of half of the form you see in Figure 13-6.
- Then `rotate_extrude()` created the 3D form by sweeping this plane around the axis.
- Because the vertical dimension would have been very large, it was multiplied by a scaling factor so that it would be printable (dimensions here are in millimeters).
- The resulting solid object was then printed upside-down from what is seen here, with the flat, circular base on the build platform.

It is very easy to play with parameters and generate a lot of different surfaces of revolution this way. Several different ones are shown in Figure 13-7.

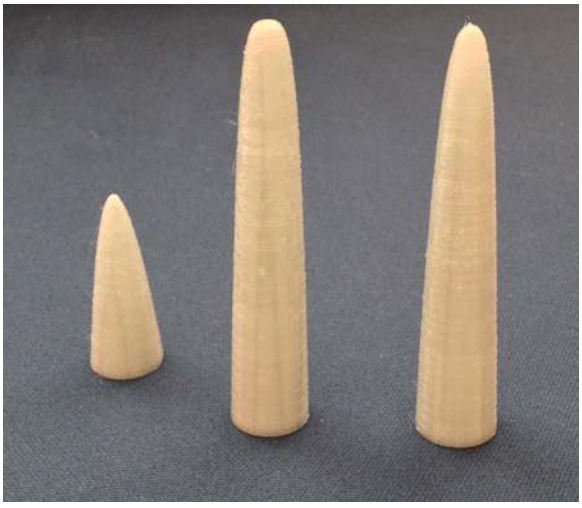


Figure 13-7. *A few different surfaces of revolution. PLA prints*

■ **Caution** OpenSCAD's `rotate_extrude()` has some limitations and cannot handle negative values in the *x* direction. *y* coordinates can be a mix of positive and negative, but all *x* values need to be greater than or less than zero to avoid generating a non-manifold mesh. If you cannot avoid that, you need to try the techniques that follow. Be sure, too, that you are not trying to generate strips of negative or zero dimensions, or for that matter, infinite dimensions.

Sinusoids

A sine wave on a screen is pretty easy to understand, but what happens in three dimensions? Or, how can you create something with structure that is not just a flat bottom? This section walks you through creating the surface $z = a\ cos(br)$, where z is the height, a and b are scaling constants, and r is the radius out from the z axis. This surface is, in principle, infinitely thin, and we want to see the top and bottom of it.

www.it-ebooks.info

In this case, rather than creating slices in a planar region and sweeping that around, we created thin concentric toroids that are raised or lowered to correspond to the surface they are modeling. Figure 13-8 shows the OpenSCAD code for this, and the top of the surface. (The bottom is the same thing seen from below.) The thin toruses are created with the code fragment

```
difference(){
cylinder(r=8*x+4.05 , h=101 , center=true);
cylinder(r=8*x-4.05, h=102 , center=true);
}
```

and moved into position to form the cosine surface with the line that precedes the `difference()` snippet:

```
translate([0,0, 100*cos(8*x)])
```

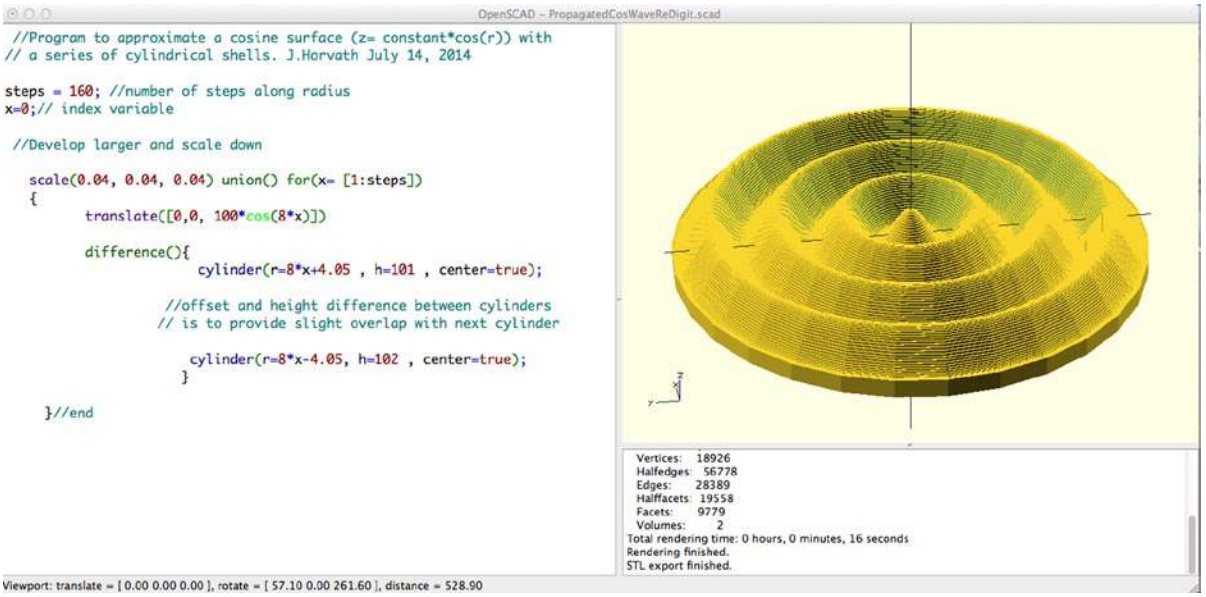

OpenSCAD – PropagatedCosWaveReDigit.scad
//Program to approximate a cosine surface (z= constant*cos(r)) with
// a series of cylindrical shells. J.Horvath July 14, 2014
steps = 160; //number of steps along radius
x=0;// index variable
//Develop larger and scale down
scale(0.04, 0.04, 0.04) union() for(x= [1:steps])
{
translate([0,0, 100*cos(8*x)])
difference(){
cylinder(r=8*x+4.05 , h=101 , center=true);
//offset and height difference between cylinders
// is to provide slight overlap with next cylinder
cylinder(r=8*x-4.05, h=102 , center=true);
}
}//end
Vertices: 18926
Halfedges: 56778
Edges: 28389
Halffacets: 19558
Facets: 9779
Volumes: 2
Total rendering time: 0 hours, 0 minutes, 16 seconds
Rendering finished.
STL export finished.
Viewport: translate = [0.00 0.00 0.00], rotate = [57.10 0.00 261.60], distance = 528.90

Figure 13-8. *OpenSCAD code to generate a cosine surface with cylindrical shells*

■ **Note** For those who have not used OpenSCAD, the small OpenSCAD examples in this section are optimized for readability. OpenSCAD power users will recognize that there are various sophisticated and cleaner ways to accomplish this. However, this implementation was designed to be as English-like as possible just to be a source of ideas about how to make models like this.

This object was sliced in standalone Cura, with a brim added (there was not enough surface area for it to stick otherwise). Full support would be impossible to get out and was not necessary. Figure 13-9 shows the model as it completed, and Figure 13-10 shows the underside before the brim—an addition on each of the circles that touched the platform—was removed.

www.it-ebooks.info

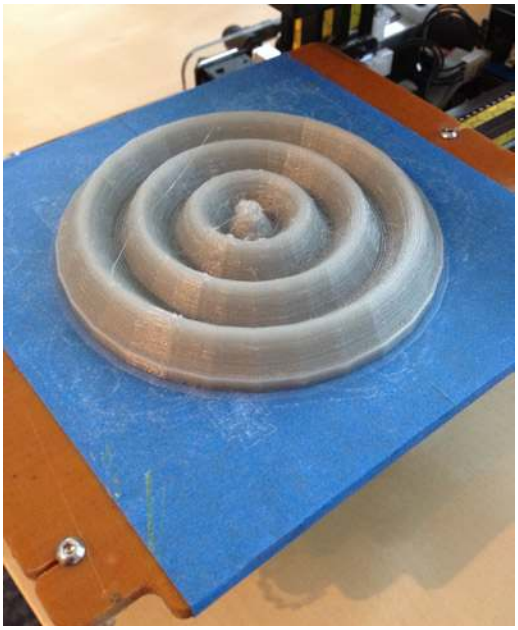


Figure 13-9. *Cosine surface model as printed. PLA print*

Figure 13-10. *Underside of the model, with brim still on it. PLA print*

■ **Tip** Some models can get quite complex and take a long time (many minutes, or hours, even on a relatively modern computer) for OpenSCAD to render. If a model is complicated, use Design ➤ Compile rather than Design ➤ Compile and Render. You will be able to see the model, but not generate an STL. To do that, you will need to let it render while you do something else.

www.it-ebooks.info

■ **Caution** You may have noticed that the strips in the surfaces of revolution example and the toruses in the sinusoidal example overlapped slightly. If you do not do that, you will generate nonmanifold models, with unpredictable results. The fact that the surface is *not* infinitely thin can cause artifacts as well.

General Surface Modeling

By now, you have seen a couple of ways of building up surfaces by stretching, moving around, or rotating basic geometric shapes. Obviously, this will work with any number of arrangements, and the best method will depend on the particulars of the abstract figure you are trying to create in 3D.

A little thought and experimentation (and probably sometimes simplification) can likely get you a long way. The smaller the pieces used to create the surface, the better the rendering will be—but the longer it will take to compile, render, and generate an STL file, and later a G-code file. Consideration also has to be given to minimizing support and to creating an object that will stick to the build platform in the first place, with assistance from a raft or brim if need be.

Other Scientific Uses of 3D Printing

3D printing can help scientists get data in the first place, in addition to visualizing and modeling. Joshua M. Pearce in his book *Open-Source Lab* (Elsevier, 2013) discusses using 3D printing as a lab tool to create equipment. Scientists themselves are developing means of 3D printing biological tissues and substrates, which we will review more in Chapter 14.

Any field that requires sharing physical samples—particularly ones that might be part of a larger picture (think paleontology or anthropology, for example)—could benefit from scanning a sample and sharing the model rather than shipping around priceless originals or plaster casts. As we noted in the section "CT Scanners" in Chapter 4, CT scans can be converted into 3D-printed models as well.

Summary

In this chapter we saw ways of using 3D printing to visualize scientific or mathematical abstractions. We learned some methods to create surfaces of revolution just using OpenSCAD and reviewed a few ways that 3D printing can be used to stock the lab itself or to share samples more effectively. Now we will look forward to conclude our adventures in 3D printing.

www.it-ebooks.info

CHAPTER 14

Futures

It is always very dangerous to predict the future of a rapidly moving field because it is very easy to be far too conservative or too aggressive. That said, this chapter picks out a few technologies, applications, and business issues that might shape the field in the longer term. There are many other possible futures out there; if you are reading this book, it is likely you, too, will have an influence!

A great deal of experimentation is going on right now in the 3D-printing space, and in the near term you are likely to see various approaches to increasing speed, and perhaps mixing subtractive and additive manufacturing methods. Just the fact that 3D printing brings together computer scientists and people who like to make things renders it a likely spawning ground for innovative ideas.

The story of any technology is the story of how and when different users adopt it. Desktop 3D printing is a classic *disruptive technology*. The term (usually credited to Harvard's Clayton Christenson) refers to any technology that is created to be a less-capable, cheaper version of an existing, expensive capability. Over time, the cheap technology gets better and starts to take over the market from the entrenched one. In the case of 3D printing, though, what is the desktop printer displacing? One could argue that commercial-grade 3D printing and conventional machining and molding all are at some risk of being displaced or at least changed. When objects can be transmitted digitally into your home, that disrupts retail and supply chains, too.

This chapter explores possible extensions of existing technology trends as well as some of the economic, social, and business issues that arise when anyone can share designs.

Technology Trends

The last few years have seen desktop 3D printers mature from purely hobbyist endeavors, requiring a significant learning curve, to far more user-friendly machines. As the desktop machines have stabilized, more aggressive users have moved off into the realm of 3D printing the very big and very small.

We explore one of the more spectacular, very large 3D printing projects first. Then we look at how the desktop environment itself is evolving in several parallel directions—some that give users more control, and some that automate the process away from the user. The realm of the micron-or-less resolution print—sometimes called *microfabrication*—remains rather exotic but will be an area to watch once it emerges from the lab.

Extreme Users

Usually we think of 3D printing as printing very delicate, small parts. Behrokh Khoshnevis is a professor of Industrial and Systems Engineering at the University of Southern California. He has developed a process he calls *contour crafting* to 3D print concrete at scales appropriate for building houses. The Contour Crafting group has even been looking into using the technique to build structures for colonies on other planets.

Figure 14-1 shows a test concrete wall created with the Contour Crafting process. Videos of it in action are available on the project's website (`http://contourcrafting.org`).

www.it-ebooks.info

Figure 14-1. *A section of 3D printed concrete wall. Courtesy of Contour Crafting*

The Contour Crafting printer in some ways looks like a giant version of the desktop 3D printers shown in the photos throughout this book, particularly the one back in Figure 2-1. An extruder head (which puts out a special concrete mix) runs back and forth on a gantry, building up a wall in the *x*-*z* plane, with the thickness of the wall in the *y* direction. The whole giant gantry is on rails that increment along in the front and back (*y*) direction, building up the side walls.

Concrete can be laid down without any forms (except for the print head that shapes the concrete as it emerges from the extruder). Rebar and other supporting material can be dropped in during fabrication. Figure 14-2 is an artist's conception of the process being used to fabricate a house. Although this is an experimental process right now, the Contour Crafting team hopes to use the technology to rapidly construct housing in areas of great need—such as after natural disasters or in areas that currently lack adequate shelter.

www.it-ebooks.info

Figure 14-2. *Artist's concept of the process of 3D printing a house. Courtesy of Contour Crafting*

Improving the User Experience

Consumer 3D printers have been evolving very rapidly, and competition on features and price is becoming fierce. If you have read this whole book to this point, you are now very aware that 3D printing is not a simple process (yet). Some manufacturers have developed simplified user interfaces, but these interfaces limit the types of objects users can print.

In other words, both the good thing and the bad thing about open source 3D printers is that a large number of parameters need to be set by the user. Over time, ways of automatically analyzing input files and optimizing a print will likely start to find their way down into the consumer space. But until that happens, you need to understand most of the parameters discussed in Chapters 5 and 6.

There has also been a lot of interest in finding ways for 3D printers to calibrate and align themselves. That is challenging to do within the cost and complexity constraints of a consumer printer, but nevertheless, various solutions are likely to emerge over the coming years.

Faster Printing

3D printing is still very slow. Prints can take hours, or even days. Some of the limitations are just physics—that a layer needs to cool before another one can be laid up on top of it. Current filament-based machines are starting to push against some of these physical limits.

Some projects (such as the prosthetic hand project described later in this chapter) are using "farms" of low-cost printers to produce significant numbers of custom products in parallel. Using many printers at a time like this may be one way to get past the inherent slow speed of filament-based prints.

Filament

As noted in Chapter 7, new filament materials are appearing on a regular basis. Filament variety will likely continue to expand as the market does, and as new users start looking for materials with particular characteristics, like higher strength, greater elasticity, good adhesion with glues, and so on.

Current 3D printers need filament with very precisely controlled diameters. This inflexibility makes it challenging to recycle filament, particularly at home. There are some efforts to design machines to recycle filament, notably the Kickstarter-funded Filastruder (`www.filastruder.com`), a machine that takes in pellets and puts out filament.

www.it-ebooks.info

Recycled filament is a bit further away still. Right now, filament costs are a very significant part of the overall cost of owning a 3D printer, and if that can be lowered (particularly for volume users), then the cost of 3D prints will fall by a lot, too.

Emerging 3D-Printing Applications

The early days of consumer-level 3D printing were dominated by hobbyist applications of the technology. Now, however, the use of 3D printers (though not necessarily consumer-level ones) has rapidly expanded into many industries, and this expansion is likely to continue. This section highlights two applications—printing food and medical applications—that have captured public attention. The phenomenal growth in applications of 3D printing is likely to continue for some time.

Printing Food

Printing food is a little challenging, both because most foods do not lend themselves into being made into prefabricated filaments, and because the whole food-extrusion chain (everything that touches whatever you are extruding) has to be food-safe. Some foods (such as chocolate) can behave similarly to thermoplastics, others can be extruded as a paste or gel, and others can be sprayed or drizzled as a liquid or powder, or deposited using a "sprinkling" or pick-and-place type of system as large solids (which may then be melted, as with topping a pizza). Many foods are already made by squirting out some of their constituents, so it depends on whether you consider a pastry chef to be "additively manufacturing" wedding cake icing.

One concept machine was developed by the Dovetailed design studio (`www.dovetailed.co`) in Cambridge, England as part of a food hackathon. It develops a raspberry (Figure 14-3) with a machine (Figure 14-4) that builds up the food piece droplet by droplet.

Figure 14-3. *A 3D-printed "raspberry." Photo courtesy of Dovetailed*

www.it-ebooks.info

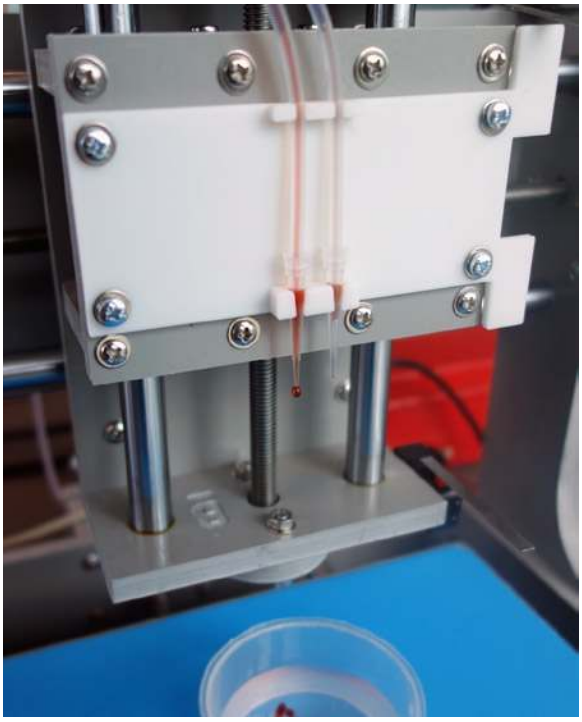


Figure 14-4. *The "fruit" 3D printer. Photo courtesy of Dovetailed*

The printer in Figure 14-4 takes tiny drops of a fruit juice mixed with a gelling solution like sodium alginate. This mix is dripped into a liquid solution to make thin-skinned droplets using a molecular gastronomy technique called *spherification.* (*Molecular gastronomy* is the use of relatively advanced chemistry and biochemistry to create novel foods, particularly identified with Nathan Myhrvold and his *Modernist Cuisine* books.)

Whether 3D printing food remains a specialty process for wedding cake toppers with mere novelty value or moves into the mainstream as a manufacturing process is something that will evolve over the coming years. Despite the challenges, there has been a lot of interest in printing pancakes, chocolate and various other foods made of sugar, and, strangely, pizza. Consumer producer Hershey's and 3D Systems announced in early 2014 that they were planning to co-develop a chocolate printer.

3D Printing in Medicine

The medical community has been very interested in 3D printing. Medicine has many problems that play to 3D printing's strengths: a need for custom devices, a lack of good, reasonably priced fabrication techniques in some cases, and a drive for lower cost everywhere. One issue, though, is whether 3D-printed parts are actually safe for medical uses.

The following Note offers details on finding further information as the rules for 3D-printed medical devices are made and commented upon by the medical community. Some issues, according to the FDA's initial workshop call, include how repeatable the manufacturing process is (repeatability is important for testing), the biocompatibility of the materials, and whether and how the materials can be sterilized adequately.

www.it-ebooks.info

■ **Note** The U.S. Food and Drug Administration (FDA), which has jurisdiction over medical devices sold in the United States, is starting to consider rules for 3D-printed medical devices. As of the writing of this book, the FDA had scheduled a workshop for October 2014 (the formal Notice is dated 5/19/2014), called Additive Manufacturing of Medical Devices: An Interactive Discussion on the Technical Considerations of 3-D Printing; Public Workshop; Request for Comments. You can read more about it here: www.federalregister.gov/articles/2014/05/19/2014-11513/additive-manufacturing-of-medical-devices-an-interactive-discussion-on-the-technical-considerations.

Bioprinting

Culturing body tissues to replace diseased or damaged body parts is not new. However, 3D printing might make the process more efficient and capable of reproducing more complex systems than has been possible before. *Bioprinting,* as the process is often called, often relies on printing some sort of scaffolding material, similar to consumer 3D printing (or squirting out some gel, like the food printer in the preceding section). The company Organovo, for example (www.organovo.com) is exploring bioprinting tissues for research, including an attempt to test the printing of liver tissue.

The bioprinting arena is expanding so rapidly that any attempt to be inclusive here will be woefully out of date within months. The open source journals *PLoSONE* (www.plosone.org) and *PLoSBiology* (www.plosbiology.org) are readily available resources to explore the state of the field beyond what you might find in a general web search; search on the keyword *bioprinting*.

■ **Tip** A good survey reference about bioprinting is a 2014 article by Jordan Miller in *PLoSBiology*, called "The Billion Cell Construct: Will Three-Dimensional Printing Get Us There?" The article is freely available at www.plosbiology.org/article/info%3Adoi%2F10.1371%2Fjournal.pbio.1001882). As Miller points out in his article, U.S. National Institutes of Health (NIH) has started a website for sharing bioprints and related models (http://3dprint.nih.gov) and has begun developing standards for the things that an STL file just cannot capture about something created partially of living cells.

The Low-Resource Health Worker

Later on in this chapter, we discuss low-cost, homebuilt prosthetics both for the developing world and for generally making lower-cost medical devices. The ability to make a medical device without training creates some interesting regulatory, ethical, and philanthropic challenges. Several organizations are looking at DIY medicine, both for resource-poor communities and to solve gaps in the day-to-day healthcare space.

The Little Devices lab at MIT has several websites, notably its main one (http://littledevices.org) and its MakerNurse site (http://makernurse.org). 3D printing is involved only as a potential part of the lab's solutions, but its sites feature some interesting early projects that you may find to be a rich source of ideas.

Low-Cost Prosthetic Hands

The 3D-printing community has developed 3D-printed prosthetic hands. Some designs have arisen from people helping out someone they know who has lost a hand but who cannot afford a conventional first-world prosthesis.

One collaboration between Richard Van As of Johannesburg, South Africa—who lost his hand in a shop accident—and special-effects professional Ivan Owen resulted in a design that was then converted to a 3D-printable version for a 5-year-old boy, Liam, and subsequently posted to Thingiverse. Robohand, as it has come to be known, is a mix of 3D-printed and CNC machine parts, as well as some conventional off-the-shelf hardware.

www.it-ebooks.info

Robohand (www.robohand.net) has continued evolving to become simpler to put together, and, according to its website, the group maintains a "print farm" of consumer 3D printers to create hands. The organization has worked with Los Angeles-based Not Impossible Labs to take the concept to Sudan to provide hands for people who lost them due to ongoing wars. Robohand has inspired others to take the plans and create their own versions. For example, e-Nable, an organization that creates 3D-printed prosthetic hands for those in need and shares its designs for free (http://enablingthefuture.org), credits the Robohand group as inspiration.

The Developing World

If 3D printers can make life more convenient and prototyping more cost-effective in the First World, what might they do in developing countries? Running a 3D printer in a region without infrastructure presents several challenges: you need to power it and you have to somehow find a way to buy or make filament. In the long run, it will be essential to find a way to recycle filament or otherwise create it locally for these markets.

The open source appropriate technology movement (notably the Michigan Tech Lab in Open Sustainability Technology, at www.mse.mtu.edu/~pearce/) has been trying to find ways to link up open source 3D printing, solar power, and ways of locally creating filament to enable manufacturing anywhere.

Cellphones and online banking took hold in Africa quickly because of the lack of other infrastructure. Time will tell whether 3D printing can become an enabling technology there in the same way. Kodjo Afate Gnikou from the West African country of Togo received a lot of press in 2013 when he built a 3D printer at the WoeLab, a hackerspace in the capital city of Lome.

The printer, built mostly out of e-waste, was one of the true *RepStrap* printers. A RepRap printer, as you learned in Chapter 1, is a printer built to replicate itself. A Rep*Strap* printer, on the other hand, is built out of whatever is lying around, just to enable 3D printing somehow (not necessarily with the intent to build more printers, per se).

Gnikou built the printer for the most part out of things he found in a dump, spending about $100 on other parts that he could not find lying around. Subsequently, WoeLab has used a crowdfunding site to build more printers based on Gnidou's design.

■ **Note** To read more about this RepStrap printer, see its crowdfunding page at www.ulule.com/wafate/.

The Business of 3D Printing

At the moment, the 3D-printing industry is split into 3D printer manufacturers and *service bureaus*—organizations that will, for a fee, 3D print an object for you. The content part of the industry—models available for printing by third parties—is still maturing. Whether the sale of 3D models becomes a significant business in its own right remains to be seen and depends to a degree on how easy to use consumer 3D printers become. Meanwhile, some basic intellectual property issues need to be sorted through.

Printer Patent Issues

Business models using 3D printing are evolving rapidly. What does the future hold for the printer industry itself? There are some crosscurrents out there right now in the business environment that will likely have a big effect on the industry going forward.

As discussed in Chapter 1's section "The RepRap Movement," consumer 3D printers largely arose because of the open availability of most of the 3D-printing technology when key patents expired. The RepRap printers evolved quickly as open source designs, and as long as it was mostly a hobbyist enterprise, there was not a lot of incentive to invest in any further patent protection.

www.it-ebooks.info

However, the tone of the discussion changed when Stratasys (the parent company of consumer 3D-printer manufacturer Makerbot) sued 3D printer maker Afinia for patent infringement of some of the remaining unexpired patents in the field. Afinia's response was to declare that the patents in question were invalid on a variety of grounds and to claim that Stratasys was attempting to create a monopoly.

As of the writing of this book, the case was still pending. There has been further distress in the open source community over patents held by some manufacturers that the community considers to be inventions that were in fact developed as open source. Sorting all this out is going to take time.

■ **Note** Afinia's response to Stratasys in its entirety is available at www.afinia.com/3d-printers-and-printing/afinia-answer-to-stratasys-claims.

Hardware as a Service

The current trend for businesses is to think of *software as a service*. That is, instead of buying software, a user subscribes to it and never actually owns it. Is 3D printing creating an era of *hardware as a service*? This might mean purchasing a design and printing it yourself, or purchasing a print created by a service bureau.

Some knotty problems arise with this business model, though. The previous section talked about patents for the printers. What about the ownership of the items being printed? At the moment, scanning a part is still a fairly painful and time-consuming process, but presumably this, too, will start to improve. The issues about who can make a copy of what (and who can sell those copies) is likely to make the digital distribution disruption in the music and publishing industries pale in comparison.

STL or G-code file sharing has some similarities with music sharing, but it takes more skill to print an object than to open an e-book or play an MP3 file. Will users (and printers) evolve so that most people print their own copies, or will they use networks of custom print shops? An explosion of business models and services seems inevitable in the coming years as people explore different routes to mass-customized products.

No matter how the business models turn out, that there will be a lot of different ones seems inevitable. We hope that you learned enough from this book to be able to come up with your own and change the world!

Summary

This chapter reviewed some usability and technology challenges that the industry is working to overcome in order to enable more broad-based use of 3D printers. This chapter also took a look at some of the many possible growth avenues of 3D printing, notably food and medical printing. Finally, it reviewed some of the difficult business issues that will need to be considered as the industry grows.

www.it-ebooks.info

APPENDIX A

Typical Printer Settings

Several chapters in this book, most notably Chapters 5 and 8, discuss settings for slicing a file. If you use Slic3r, you may be intimidated by all the settings you see in the Configure panel. The Slic3r manual (http://manual.slic3r.org/) defines all these in detail, and we will not reproduce those definitions here.

Printer settings are something that, like recipes, you will experiment with and evolve over time. The *Slic3r* settings provided here are appropriate for a Deezmaker Bukobot, which is a fairly typical RepRap printer, except perhaps for having somewhat higher speeds than some. The author thanks Rich Cameron for developing these standard "starter" settings, and Deezmaker for sharing them.

Note To get a more current settings file (since the slicing software and community practices change) go to www.bukobot.com, click on a printer, and then click *Settings*. Directions for downloading the latest complete set will appear. Your manufacturer likely has a similar page, but if not, this chapter will give you some plausible starting points.

Slic3r Typical Settings

Three *Slic3r* cases are given here: for an "easy print" that does not need any support, for a print that does need support, and for a vase. These settings might not match every value used in Chapter 8 for similar prints, because each print may need a bit of optimization. Over time, you will decide which settings to change and which ones generally to leave alone.

Of course, Slic3r is open source software, and both the settings names and behavior associated with a particular value will change over time. The various host programs give access to Slic3r parameters in different formats; see Chapter 6 for a discussion of Repetier Host and Matter Control, and Chapter 8 for Matter Control screenshots.

Slicing settings are typically grouped by the software into Printer, Print, and Filament parameters. Printer settings usually are associated with a machine and do not change much from print to print. In Table A-1, we have the standard settings for a Bukobot, which has an 8 inch (200 mm) cubic print bed.

Values for physical dimensions (e.g. layer height) in the following tables are given in mm; temperatures are in degrees Centigrade.

www.it-ebooks.info

Table A-1. *Printer Settings (Regardless of What Is Being Printed—Machine-Dependent)*

General	
Bed size, x	200
Bed size, y	200
Print center, x	100
Print center, y	100
Z offset	0
G-code flavor	RepRap (Marlin/Sprinter) *(But see your manufacturer just in case)*
Use relative E distances	Unchecked
Extruders	1
Vibration limit	0
Custom G-code	
*See manufacturer's suggestions**	
Extruder	
Size: Nozzle diameter	See manufacturer's specification
Position: Extruder offset, x	0
Position: Extruder offset, y	0
Retraction: Length	1.4
Retraction: Lift Z	0
Retraction: Speed	Ranges from 10-200 mm/s
Retraction: Extra length on restart	0
Retraction: Minimum travel after retraction	2
Retraction: Retract on layer change	Checked

**Custom G-code can include things like homing all axes before a print, turning off heaters after, and the like.*

Filament settings are tied to the filament; each printer typically uses just one size of filament (here, 3 mm, measured to be 2.85mm actual diameter). A 2.85mm nominal diameter is common for what is normally called "3mm" filament. It's a bit of an accident of history (and convenient imperial drill sizes) that 3mm, in this case, is considered an upper safe limit to allow tolerance for the filament to move without jamming. The same is not true for 1.75mm filament, which almost always has a nominal diameter of 1.75 (or, occasionally, 1.8). The other filament settings that normally needs to be input by a user are the extruder and heated bed temperatures associated with that material,and sometimes an adjustment for the cooling settings (although this last is an expert-level adjustment).

Table A-2 shows the settings for PLA. See Chapter 7, Table 7-1, for settings for different filament materials.

www.it-ebooks.info

Table A-2. *Filament Settings*

Filament Settings	**PLA**
Filament: Diameter	2.85*
Filament: Extrusion multiplier	1
Temperature: Extruder: First layer	210
Temperature: Extruder: Other layers	210
Temperature: Bed: First layer	60 (or 0 for unheated bed)
Temperature: Bed: Other layers	60 (or 0 for unheated bed)
Cooling Settings	
Enable cooling	Checked
Fan settings: Fan speed min	35
Fan settings: Fan speed max	100
Fan settings: Bridges fan speed	100
Fan settings: Disable fan for the first ___ layers	1
Keep fan always on	Unchecked
Cooling thresholds: Enable fan if layer print time is below __ approximate seconds	60
Cooling thresholds: Slow down if layer print time is below __ approximate seconds	35
Cooling thresholds: Min print speed	10

**Ideally, you should measure actual filament diameter with calipers (Chapter 7).*

The majority of the settings are in the Print category. In Table A-3 we split them into settings that do not typically change from one run to another, and in Table A-4 into ones that would be different among the simple, vase, and support prints.

www.it-ebooks.info

Table A-3. *Printer Settings that Typically Do Not Change from Run To Run*

Output Options	
Complete individual objects	Unchecked
Extruder clearance	Ignored if previous item unchecked
Advanced	
Default extrusion width	0 (Slic3r will use defaults)
First layer (use % if %)	200 %
Perimeters	0
Infill	0
Solid infill	0
Top solid infill	0
Support material	0
Bridge flow ratio	1
Threads	4
Resolution	0

Table A-4. *Printer Settings that Vary Among the Simple, Vase, and Support Prints*

Recommended Material Layers and Perimeters	Low Res, Simple Print ABS/PLA	Overhangs (Support)/High Res ABS Preferred	Vase (Spiral Build) ABS/PLA
Layer height	0.3	0.15	0.25
First layer height	0.3	0.3	0.3
Perimeters	2	2	1
Random start points	Checked	Checked	Checked
Generate extra perim	Checked	Checked	Checked
Solid layers, top	4	8	0
Solid layers, bottom	4	6	4
Avoid crossing perimeters	Unchecked	Unchecked	Unchecked
External perimeters first	Unchecked	Unchecked	Unchecked
Infill			
Fill density (%)	15	15	0
Fill pattern	Honeycomb	Honeycomb	Honeycomb
Top/bottom fill pattern	Rectilinear	Rectilinear	Rectilinear
Infill every	1	2	1
Only infill when needed	Unchecked	Unchecked	Unchecked

(*continued*)

www.it-ebooks.info

Table A-4. (*continued*)

Recommended Material Layers and Perimeters	Low Res, Simple Print ABS/PLA	Overhangs (Support)/High Res ABS Preferred	Vase (Spiral Build) ABS/PLA
Solid infill every	0	0	0
Fill angle	45	45	45
Solid infill threshold area	7	7	7
Only retract when crossing perimeters	Checked	Checked	Checked
Infill before perimeters	Unchecked	Unchecked	Unchecked
Speed			
Perimeters	60	60	40
Small perimeters	60	60	40
External perimeters	60	60	40
Infill	80	80	80
Solid infill	80	80	60
Top solid infill	60	60	60
Support material	60	60	60
Bridges	30	30	30
Gap fill	20	20	20
Travel	150	150	150
First layer speed (note: add % if %)	30 %	30 %	30 %
Skirt and Brim			
Loops	2	2	2
Distance from object	2	2	2
Skirt height	1	1	1
Min extrusion length	0	0	0
Brim width	0	0	0
Support Material			
Generate support material	Unchecked	Checked	Unchecked
Overhang threshold	(Rest of params ignored)	0	(Rest of params ignored)
Enforce support for first		0	
Raft layers		0	
Pattern		Rectilinear	
pattern spacing		4	
Pattern angle		0	
Interface layers		3	
Interface pattern spacing		0	

www.it-ebooks.info

Cura Settings Differences

There are other slicing programs besides Slic3r, notably Cura (see Chapter 5 for more about Cura). Cura has fewer user-alterable settings than does Slic3r. However, it tends to be more forgiving of mesh errors and very large files. Cura allows the creation of support only where it touches the platform, which is often very useful, to avoid having support where it might not be needed but would be hard to extract. Another crucial difference between Slic3r and Cura is that in Cura you specify the wall thickness and solid surface thickness in millimeters, not in perimeters or layers.

In Cura, under Support, there are these options:

- Support type
  - None
  - Touching Buildplate
  - Everywhere
- Platform adhesion type
  - None
  - Brim
  - Raft

The Touching Buildplate option allows for building support only under the object—sort of like a shaped raft. This option avoids picking support out of complicated structures farther up the print where you might get away without it. These options collectively give you a lot of flexibility to support your print without having to invest an inordinate amount of time picking off that support. Other than the support, the settings are named similarly to those in Slic3r, but with fewer available for user alterations.

www.it-ebooks.info

APPENDIX B

Links and Resources

This appendix aggregates all the links in the book for your convenience and adds a few additional sites that were not called out explicitly in the text. If a link appears in more than one chapter, it is just listed here the first place that it appears. General interest media sites are aggregated at the end, regardless of where they first appeared.

Chapter 1: A Brief History of 3D Printing

How seashells are created: www.scientificamerican.com/article/how-are-seashells-created/
Concrete printing: www.contourcrafting.org
RepRap project description: http://en.wikipedia.org/wiki/RepRap_Project
RepRap family tree: http://reprap.org/wiki/RepRap_Family_Tree
Kickstarter (crowdfunding site): www.kickstarter.com
Indiegogo (crowdfunding site): www.indiegogo.com
Arduino: www.arduino.cc
Gihub: https://github.com
RepRap wiki: http://reprap.org
Deezmaker 3D printers: www.deezmaker.com
RepRap Wallace printer: http://reprap.org/wiki/Wallace

Chapter 2: The Desktop 3D Printer

Nicholas Seward's page on non-Cartesian designs: http://conceptforge.org
SeeMeCNC (Deltabot printers): http://seemeCNC.com

Chapter 3: Open Source

GNU licenses: www.gnu.org/licenses/license-recommendations.html
Creative Commons licenses: http://creativecommons.org/licenses/
Wikipedia: www.wikipedia.org
Wikipedia versus Brittanica accuracy controversy: www.nature.com/nature/britannica/index.html
Github guide to open source contribution: https://guides.github.com/activities/contributing-to-open-source/
Maker Faires: www.makerfaire.com
Qtechknow electronics: http://qtechknow.com
DIY Girls nonprofit organization: www.diygirls.org
Instructables DIY site: www.instructables.com

www.it-ebooks.info

Chapter 4: Making a 3D Model

The MeshLab program: http://meshlab.sourceforge.net
Autodesk 123D Catch: www.123dapp.com/catch
Thingiverse printable design site: www.thingiverse.com
Youmagine printable design site: www.youmagine.com
Database of protein structures, the Protein Databank: www.rcsb.org/pdb/
Chimera molecular modeling software: www.cgl.ucsf.edu/chimera/
Visual Molecular Dynamics (VMD) modeling software: www.ks.uiuc.edu/Research/vmd/
Tinkercad online beginner CAD software: www.tinkercad.com
OpenSCAD open source programming CAD interface: www.openscad.org
FreeCAD open source engineering-oriented CAD program: www.freecadweb.org
Mathematica mathematics modeling software: www.wolfram.com/mathematica/
Zbrush sculptural modeling program: www.zbrush.com
Blender open source visual-effects-oriented modeling program: www.blender.org
CGcookie online learning site (good for Blender): www.cgcookie.com
Leonar3do sculptural modeling software/hardware: www.leonar3do.com
Leopoly sculptural modeling website: www.leopoly.com

Chapter 5: Slicing a 3D Model

The Slic3r slicing program: www.slic3r.org
The Cura slicing program: http://software.ultimaker.com
The Repetier Host hosting program: www.repetier.com
The Matter Control hosting program: www.mattercontrol.com

Chapter 6: Driving Your Printer: G-Code

G-Code RepRap wiki: http://reprap.org/wiki/G-code
Octoprint, host program for low-compute-resource situations: www.octoprint.org

Chapter 7: Material Considerations

UFID filament standard: http://ufids.org/ or https://github.com/camerin/UFIDS_pages
Black nylon dress: www.michaelschmidtstudios.com
Public Library of Science (PloS) journal: www.plosone.org
Conductive filament article: www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0049365

Chapter 8: Case Studies

Heart pendant STL: https://tinkercad.com/things/9fjmzUPBmR9
Gimbal STL: www.youmagine.com/designs/bukito-gimbal-demo-print
Deezmaker Bukobot wiki: www.bukobot.com

www.it-ebooks.info

Chapter 9: Moving to Metal

No new links.

Chapter 10: Large Prints and Post-Processing

No new links.

Chapter 11: Troubleshooting

Nozzle-unclogging procedure: www.bukobot.com/nozzle-cleaning

Chapter 12: Printers in the Classroom

Hackerspace directory: http://hackerspaces.org/wiki/List_of_Hacker_Spaces
William Hand boat design collection: www.handdavisyachtdesigns.org
Hart Nautical Collections, MIT Museum: http://web.mit.edu/museum/collections/nautical.html
Herreshoff Legacy Project at the MIT Museum: http://herreshoff-legacy.mit.edu/
Herreshoff Marine Museum: herreshoff.org
Cambridge Science Festival: http://cambridgesciencefestival.org
Digital Image and Graphic Resources for Accessible Materials: http://diagramcenter.org
Young Makers: http://youngmakers.org/

Chapter 13: Scientific Visualization

Worldwide Protein Databank, www.wwpdb.org
Page of links of moledular modeling software:
www.rcsb.org/pdb/101/static101.do?p=software/software_links/molecular_graphics.html
Nano-DNA: www.wired.com/2009/08/nanodna/
Rothemund's 2008 TED talk on DNA folding: www.ted.com/talks/paul_rothemund_details_dna_folding
Scholarly paper on DNA folding: http://pubs.acs.org/doi/abs/10.1021/nl050084f
Mind Research Institute: www.mindresearch.net
Parabola manipulative instructions: www.youtube.com/watch?v=PmrzcR4H6xw
Download site for parabola manipulative: www.thingiverse.com/thing:186452
TedX talk on JiJi Math: www.youtube.com/watch?v=2VLje8QRrwg

Chapter 14: Futures

Filastruder filament-making machine: www.filastruder.com
Dovetailed, a Cambridge (UK) design firm, involved with "fruit printing": www.dovetailed.co
FDA site on 3D printing-related rules discussions: www.federalregister.gov/articles/2014/05/19/2014-11513/additive-manufacturing-of-medical-devices-an-interactive-discussion-on-the-technical-considerations
Company looking at 3D printing living tissues: www.organovo.com
Public Library of Science open-access biology journal: www.plosbiology.org
Survey article on bioprinting: www.plosbiology.org/article/info%3Adoi%2F10.1371%2Fjournal.pbio.1001882

www.it-ebooks.info

National Institute of Health 3D-printing site: http://3dprint.nih.gov/
MIT-based low-resource healthcare group: http://littledevices.org/
Project to capture nurses who use DIY tactics: http://makernurse.org/
Robohand 3D-printed prosthetic hand: www.robohand.net
e-Nable robotic 3D-printed hand: http://enablingthefuture.org
Michigan Tech Open Source Appropriate Technology site: www.mse.mtu.edu/~pearce/Index.html
Crowdfunding site for African 3D printer: www.ulule.com/wafate/
Stratsys v. Afinia lawsuit: www.afinia.com/3d-printers-and-printing/afinia-answer-to-stratasys-claims

Media Sites Focusing on 3D Printing

This last group of sites are media organizations that focus on 3D printing and/or the maker movement. Many blogs and informal sites as well as major news organizations cover 3D printing. A web search on the topic of interest will reveal a mix of traditional and upstart media coverage.
3D Printer World (industry website): www.3dprinterworld.com
3D Printing Industry (industry website): http://3dprintingindustry.com
Make magazine (website and physical magazine): www.makezine.com
Hackaday (website): www.hackaday.com
3Ders (websites and community forums): www.3ders.org

www.it-ebooks.info

Index

A, B

Abstract base, 96
Acetone Slurry, 132

C

Cartesian printers, 13
Casting, 191
  lost-wax investment casting, 113
  sand casting process, 113
  vs. metal printing, 128
  searching, 128
Computer-aided design (CAD) programs, 33, 37
Computer numerically controlled (CNC), 163
Crowdfunding platform, 7
CT scanners, 35
Cura settings, 188

D, E

Deltabots, 13–14
Digital light projection (DLP), 5
Dual extruders
  support material, 107
  twocolors/materials
    Kaptontape platform, 110
    OpenScad code, 108
    Slicr3r settings, 109

F

Filament, 77, 190
  characteristics, 83
  dissolvable support, 86
  dual-extruder, 86–87
  materials
    acrylonitrile butadiene styrene (ABS), 84
    nylon, 84
    polycarbonate, 85
    polylactic acid (PLA), 83
    research filaments, 85
    T-glase (PET), 85
    thermoplastic elastomers (TPEs), 85
  multiple extruders, 86
  PLA fan, 81
  polylactic acid (PLA) filament, 77
  quality control
    diametres, 78
    directional strength, 80
    erratic print quality, 79
    extruder nozzles, 79
    print bed, 80
    storing and handling, 82
    thermoplastic elastomers (TPEs), 79
    ventilation and drafts, 81
  spools of nylon, 77
  Uniform Filament Identification system (UFID), 78

G, H, I, J, K

G-code, 190
  CNC market, 66
  commands, 66
  during print, 71
  host program
    MatterControl host, 69
    Octoprint, 70
    Repetier host, 67
  manual controls, 72
    changing filament, 73
    kill job/stop button, 73
    temperature changes, 74
    trouble shooting, 74

www.it-ebooks.info

G-code (*cont.*)
microSD card, 76
printer's firmware, 70
print finishes
build platform, 71
painstaking process, 72
restarting or shutting, 72
Slic3r program, 68
3D printer
firmware, 65
hardware and
software architecture, 66
microSD card, 66
tool change command, 67

L

Layer height, 55
Lost-wax investment casting
lost-PLA process, 127
variations, 126

M, N

MeshLab, 130

O

OpenSCAD, 38
Open source, 21, 189
infrastructure
forums, 23–24
GNU licenses, 22
open source repositories, 23–24
pros and cons, 25
wikis (*see* Wikipedia)
3D-printing community
contribution, 29
hackerspaces/makerspaces, 27
maker movement, 25

P, Q, R

Polylactic acid (PLA), 51
Print bed
blue painter's tape, 80
Kapton tape, 81
Printer
Infill, 186
layers and perimeters, 186
recommended material, 186
skirt and brim, 187
speed, 187
support material, 187
Protein databank (PDB), 36

S

Sand casting process
boat and sprues, 123
flask filling
backing board, 116
parting compound, 117
runners, 120
sprue cutter, 120
with molten aluminum cooling, 122
layer orientation, 125
pattern, 113
patterns, 125
Petrobond, 114
PLA patterns, 115
shrinkage and clearances, 125
sprues printing, 126
terminology, 114
undercuts, 125
Scientific visualization, 191
mathematicians, 167
general surface modeling, 174
generatrix, 170
OpenSCAD, 170
parabola math manipulative, 168
sinusoids, 171
molecular biologists, 165
DNA origami, 166
model accuracy considerations, 166
Selective laser sintering (SLS), 5
Simple print
heart pendant
filament settings, 94
Infill settings, 92
layers and perimeters, 92
layer view simulation, 95
MatterControl 3D viewer, 94
MatterControl screen, 91
real printer, 94
skirt and brim settings, 93
support material settings, 93
Slic3r typical settings, 183
filament, 184
Printer, 184, 186
Slicing, 190
cutting model, 55
definition, 47
gimbal, 101
layer height effects, 55
matter control, 48
orientation model, 53
post-processing, 48
Slic3r program
downloading, 60
filament settings, 61

www.it-ebooks.info

open source Cura program, 63
printer settings, 61
print settings, 61
Repetier Host program, 61
speed
bridging, 57
infill, 59
perimeter, 58
retraction, 59
supported model, 52
tools and techniques, 48
brims, 49
heated platforms, 51
PLA models, 51–52
rafts, 51
skirts, 50
Stereolithography (SLA), 5
Surface Tesselation Language (STL), 33

T, U, V

3D model, 33, 190
CAD programs
architectural project, 42
cubes, 38
engineering tool, 42
OpenSCAD, 38
sculptural models, 41
sculptural tools, 43
Tinkercad, 37
visual-effects developers, 42
existing models
protein databank (PDB), 36
STL file, 36
scanning
consumer-level, 35
CT scanners, 35
point cloud, 34
stray reflections, 34
3D printer
consumer-level printers, 45
manifold object, 34
speed *vs*. customization, 45
surface tesselation language (STL), 33
watertight object, 34
3D printers, 11, 189, 191
build platform, 16
challenges, 161
CNC, 163
control electronics, 19
DIY Girls, 163
early-adopter experiences, 164
extruder design
Bowden extruder, 17
direct-drive extruder, 17
nozzles, 17
retraction, 17
filament, 16
filament-based consumer printers
Cartesian, 13
Deltabots, 13–14
frame, 16
full-hull models, 156, 160
Hand speedboat, 161
Hart Nautical collections, 154
Herreshoff cleat, 158
kits *vs*. assembled, 16
machine tools, 19
MIT Museum, 160
opportunities, 161
personalization, 12
program makers, 163
robotics clubs and team, 162
safety and ventilation, 19
sketchup program, 156
stepper motors, 17
tactile learners, 162
teaching
CAD program, 151
engineering and design classes, 153
student designs, 152
uses, 11
3D printing, 174, 189–190. *See also* Scientfic visualization
additive manufacturing, 5
Arduino, 8
Bear platform
build up, 106
completed bear, 106
MatterControl's visualization, 103
MatterSlice support, 105
support material, 104
tail down, 104
big objects
acetone slurry, 132
build platform, 130
cutting process, 131
gluing, 131
clogged nozzle solutions, 142
cold-pull technique, 143
drive gear teeth clogged, 146
wire brush bristle, 145
complex objects, 129
description, 3
digital light projection, 5
disruptive technology, 175
dual extruders
support material, 107
twocolors/materials, 108
dyeing nylon, 135
environmental issues

www.it-ebooks.info

3D printing (*cont.*)
ambient temperature, 138
drafts, 138
dust-catcher, filament, 139
humidity, 139
evolution of, 9
future aspects, 181, 191
Gimbal
layers and perimeters, 101
layer visualizations, 101
object settings, 101
on printer, 103
slicing, 101
three-ring, 100
two axes, 103
Github, 8
hand-building support, 107
in medicine, 179
bio printing, 180
medical devices, 180
prosthetic hands, 180
MeshLab, 130
nature's 3D printers, 3
painting ABS and PLA, 135
printer patent issues, 181
printing food, 178
robotic 3D printers
contour crafting, 6
crowdfunding, 7
history of, 6
RepRap movement, 7
two-photon polymerization, 6
sanding, 132
selective laser sintering, 5
services, 182
simple print, 89
abstract base, 96
Heart pendant, 90
slicing (*see* Slicing)
smoothing and bonding ABS, 133
speed settings, 110
stereolithography, 5
technology trends
contour crafting, 175
faster printing, 177
filament, 177
microfabrication, 175
user experience, 177
troubleshooting, 191
clicking/grinding noises, 137
designed to fail, 141
eliminate stringing, 146
feeler gauge, 140
software upgrades, 146
squaring, 140
tramming the platform, 140
vase printing, 98

W, X, Y

Wikipedia
RepRap project, 24
wiki accuarcy, 23

Z

Zbrush, 42

www.it-ebooks.info

Mastering 3D Printing

Joan Horvath

Apress®

www.it-ebooks.info

Mastering 3D Printing

Copyright © 2014 by Joan Horvath

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

ISBN-13 (pbk): 978-1-4842-0026-1

ISBN-13 (electronic): 978-1-4842-0025-4

Trademarked names, logos, and images may appear in this book. Rather than use a trademark symbol with every occurrence of a trademarked name, logo, or image we use the names, logos, and images only in an editorial fashion and to the benefit of the trademark owner, with no intention of infringement of the trademark.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Publisher: Heinz Weinheimer
Lead Editor: Michelle Lowman
Technical Reviewer: Richard Cameron
Developmental Editor: Anne Marie Walker
Editorial Board: Steve Anglin, Mark Beckner, Ewan Buckingham, Gary Cornell, Louise Corrigan, Jim DeWolf, Jonathan Gennick, Jonathan Hassell, Robert Hutchinson, Michelle Lowman, James Markham, Matthew Moodie, Jeff Olson, Jeffrey Pepper, Douglas Pundick, Ben Renow-Clarke, Dominic Shakeshaft, Gwenan Spearing, Matt Wade, Steve Weiss
Coordinating Editor: Kevin Walter
Copy Editor: Corbin Collins
Compositor: SPi Global
Indexer: SPi Global
Artist: SPi Global
Cover Designer: Anna Ishchenko

Distributed to the book trade worldwide by Springer Science+Business Media New York, 233 Spring Street, 6th Floor, New York, NY 10013. Phone 1-800-SPRINGER, fax (201) 348-4505, e-mail orders-ny@springer-sbm.com, or visit www.springeronline.com. Apress Media, LLC is a California LLC and the sole member (owner) is Springer Science + Business Media Finance Inc (SSBM Finance Inc). SSBM Finance Inc is a Delaware corporation.

For information on translations, please e-mail rights@apress.com, or visit www.apress.com.

Apress and friends of ED books may be purchased in bulk for academic, corporate, or promotional use. eBook versions and licenses are also available for most titles. For more information, reference our Special Bulk Sales–eBook Licensing web page at www.apress.com/bulk-sales.

Any source code or other supplementary material referenced by the author in this text is available to readers at www.apress.com. For detailed information about how to locate your book's source code, go to www.apress.com/source-code/.

www.it-ebooks.info

For Thomas MacCalla and Jacqueline Caesar, who taught me what it really means to be an educator.

www.it-ebooks.info

Contents

About the Author xvii

About the Technical Reviewer xix

Acknowledgments xxi

Introduction xxiii

Part 1: Open Source 3D Printers 1

Chapter 1: A Brief History of 3D Printing 3

What Is 3D Printing? 3

Nature's 3D Printers 3

Historical Additive Manufacturing 5

Types of 3D Printers 5

The Early Days of Robotic 3D Printers 6

The RepRap Movement 7

The Rise of Crowdfunding 7

Enabling Technologies 8

The Arduino 8

Open Source Code Repositories 8

A Case Study of Printer Evolution 8

Summary 10

Chapter 2: The Desktop 3D Printer 11

Who Uses Consumer 3D Printers? 11

Types of Filament-Based Consumer Printers 13

Cartesian Printers 13

Deltabots 14

www.it-ebooks.info

Kits vs. Assembled Printers....16
3D Printer Design Considerations....16
Filament....16
Frame....16
Build Platform....16
Extruder Design....17
Moving Parts....17
Control Electronics....19
Machine Tool or Computer Peripheral?....19
Safety and Ventilation....19
Summary....20

Chapter 3: Open Source....21

Open Source Infrastructure....22
GNU Licenses....22
Wikis, Forums, and Open Source Repositories....23
Open Source Pros and Cons....25
Meeting the Open Source 3D-Printing Community....25
The Maker Movement....25
Makerspaces and Hackerspaces....27
Contributing to the Open Source Community....29
Summary....29

Part 2: The 3D Printing Process....31

Chapter 4: Making a 3D Model....33

What Makes A Model Printable on A 3D Printer?....33
3D Model File Formats....33
What Does “Watertight and Manifold” Mean?....34
Scanning a Model....34
Consumer-Level 3D Scanners....35
CT Scanners....35

www.it-ebooks.info

Downloading and Modifying Existing Models....36
Models of Everyday Things....36
Specialized Databases....36
Creating a New Model....37
Using a CAD Program....37
Programs for Specific Applications....41
Design Considerations....44
Complexity Is Free: Hardware as a Service....45
Speed vs. Customization....45
Summary....46
Chapter 5: Slicing a 3D Model....47
What Is "Slicing?"....47
3D Printing as Cooking....47
Tools and Techniques....48
Starting a Print and Getting a Model to Stick to the Platform....49
Supporting and Orienting a Model....52
Effects of Layer Height....55
Speed....57
Managing Internal Open Space....57
Getting Started: How to Slice an Object....60
Slicing Programs: Slic3r....60
Alternative Hosting and Slicing Programs....63
Summary....63
Chapter 6: Driving Your Printer: G-code....65
Controlling Your 3D Printer....65
Understanding G-code....66
Using Host Programs....67
Repetier Host....67
MatterControl....69
Octoprint....70

www.it-ebooks.info

When a Print Starts 70
During a Print 71
When a Print Finishes Normally 71
Getting a Part off the Build Platform 71
Picking Off Support and Cleaning Up The Print 72
Restarting or Shutting Off the Printer 72
Manually Controlling Your Printer 72
Stopping a Print 73
Changing Filament 73
Changing Temperatures During a Print 74
Basic Hardware Troubleshooting 74
Running from an SD Card 76
Summary 76

Chapter 7: Material Considerations 77

Filament Quality Control 78
Selecting and Using a Filament 79
Temperature and Speed Settings 82
Will My Filament Spool Run Out During My Print? 83
Filament Materials 83
Polylactic Acid (PLA) 83
Acrylonitrile Butadiene Styrene (ABS) 84
Nylon 84
T-glase (PET) 85
Polycarbonate 85
Thermoplastic Elastomers (TPEs) 85
Research Filaments 85
Multiple Extruders 86
Printing Dissolvable Support 86
Dual-Extruder Printing with Two Different Materials 86
Summary 87

www.it-ebooks.info

Chapter 8: Case Studies 89
Simple Print 89
Simple Print Example 1: Heart Pendant 90
Simple Print Example 2: Abstract Base 96
Printing a Vase 98
Printing a Complex Object with Fine Detail 100
Printing with Support 103
Hand-Building Support 107
Dual Extruders 107
Dual Extruders: Using One Head for Support Material 107
Dual Extruders: Models in Two Colors (or Two Materials) 108
Speed Settings 110
Summary 110

Part 3: 3D Printing Meets Traditional Prototyping 111

Chapter 9: Moving to Metal 113
The Sand-Cast Process 113
Sand-Casting Terminology 114
Patterns Made from PLA 115
Filling the Flask with Sand 116
Cutting Sprues and Runners 120
Pouring in the Metal 122
Finishing the Sand Casting 122
Planning Ahead for Better Casting 123
Adding Draft to Patterns 125
Avoiding Undercuts 125
Layer Orientation 125
Shrinkage and Clearances 125
Printing Your Sprues? 126
Investment Casting 126
Lost-PLA Process 127

www.it-ebooks.info

Casting vs. Printing in Metal 128
Finding Casting Services 128
Summary 128

Chapter 10: Large Prints and Post-Processing 129
Printing Computationally Complex Objects 129
Printing Physically Big Objects 130
Objects That Are Too Long for the Build Platform 130
Objects That Are Too Big in More Than One Dimension 131
Gluing the Pieces Together 131
Sanding, Chemical Smoothing, Painting, and Dyeing 132
Sanding 132
Smoothing and Bonding ABS with Acetone 133
Painting ABS and PLA 135
Dyeing Nylon 135
Summary 135

Chapter 11: Troubleshooting 137
Clicking or Grinding Noises 137
Environmental Issues 138
Drafts 138
Ambient Temperature 138
Humidity 139
Dust 139
Printer Internal Alignment Issues 140
Prints Not Sticking to the Build Platform 141
Clogged Nozzle Solutions 142
Cold Pull 143
Wire Brush Bristle 145
Extruder Drive Gear Teeth Clogged 146

www.it-ebooks.info

Eliminate Stringing 146
Software Upgrades 146
Summary 147

Part 4: Using Your Printer 149

Chapter 12: Printers in the Classroom 151

Teaching Design, Engineering, and Art 151
Hands-on History 154
William Hand, Jr. Boat Hull 154
Herreshoff Cleat 157
Reactions to the 3D Prints 160
Learning Through Re-Creating History 161
The Special-Needs Student 162
After-School Activities 162
Robotics Clubs and Teams 162
DIY Girls 163
Young Maker Programs 163
Career Tech Ed 163
Early-Adopter Experiences 164
Summary 164

Chapter 13: Scientific Visualization 165

Visualizing Molecular Biology 165
Model Accuracy Considerations 166
Example: 3D-Printed Models of Six-Helix DNA Bundles 166
Visualizing Mathematical Abstractions 167
Parabola Math Manipulative 168
Surfaces of Revolution 170
Sinusoids 171
General Surface Modeling 174
Other Scientific Uses of 3D Printing 174
Summary 174

www.it-ebooks.info

Chapter 14: Futures 175
Technology Trends 175
Extreme Users 175
Improving the User Experience 177
Faster Printing 177
Filament 177
Emerging 3D-Printing Applications 178
Printing Food 178
3D Printing in Medicine 179
The Developing World 181
The Business of 3D Printing 181
Printer Patent Issues 181
Hardware as a Service 182
Summary 182

Appendix A: Typical Printer Settings 183
Slic3r Typical Settings 183
Cura Settings Differences 188

Appendix B: Links and Resources 189
Chapter 1: A Brief History of 3D Printing 189
Chapter 2: The Desktop 3D Printer 189
Chapter 3: Open Source 189
Chapter 4: Making a 3D Model 190
Chapter 5: Slicing a 3D Model 190
Chapter 6: Driving Your Printer: G-Code 190
Chapter 7: Material Considerations 190
Chapter 8: Case Studies 190
Chapter 9: Moving to Metal 191
Chapter 10: Large Prints and Post-Processing 191
Chapter 11: Troubleshooting 191

www.it-ebooks.info

Chapter 12: Printers in the Classroom....191
Chapter 13: Scientific Visualization....191
Chapter 14: Futures....191
Media Sites Focusing on 3D Printing....192

Index....193

www.it-ebooks.info

About the Author

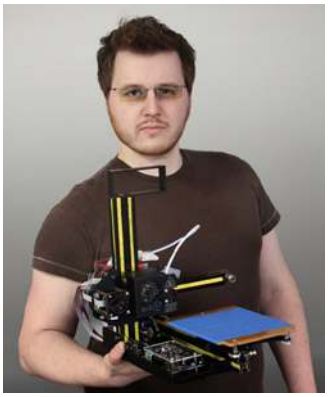
Joan Horvath has been an engineer, educator, and management consultant. She was an early member of the management team at Deezmaker, a startup 3D printer company. She also has an appointment as Core Adjunct faculty for National University's College of Letters and Sciences, where she teaches online in the Interdisciplinary Studies program. She has taught at the university level for several institutions, both in Southern California and online, and has been involved in various entrepreneurial ventures.

Before becoming an entrepreneur, she spent the first 16 years of her professional life at the NASA/Caltech Jet Propulsion Laboratory (JPL). There, she worked in programs that included the technology transfer office, the Magellan spacecraft to Venus, the TOPEX/Poseidon oceanography spacecraft, and a program to develop technology to explore the ice-covered oceans on Jupiter's moon, Europa.

Joan holds an undergraduate degree from MIT in Aeronautics and Astronautics and a master's degree in engineering from UCLA. She has coauthored an art book on Saturn, authored a book about what scientists actually do, and is the author or coauthor of various technical papers. She is engaged in many volunteer activities, frequently in a leadership role. Some of her current and past positions include: President of the MIT Class of 1981, VP Communications of the MIT Club of Southern California, FIRST Robotics Southern California Regional judge, member of the Executive Committee of the Caltech Entrepreneurs Forum, and full-garden docent and member of the Botanical Volunteer Board at the Huntington Library, Art Collections and Botanical Gardens in San Marino. She lives in Pasadena with her astronomer husband and way too many books.

www.it-ebooks.info

About the Technical Reviewer



Rich Cameron (known online as "Whosawhatsis") is the Vice President of Research and Development at Deezmaker 3D Printers and the designer of the Bukito portable 3D printer (pictured on the cover of this book). Rich is an experienced open source developer who has been a key member of the RepRap printer development community for many years. Rich personally built several of the early, classic 3D printers and wrested amazing performance out of even those ancestral machines. When he's not busy making every aspect of his own 3D printers better, from slicing software to firmware and hardware, he likes to share that knowledge and experience so that he can help make everyone else's printers better too.

www.it-ebooks.info

Acknowledgments

This book would never have been written without the help, patience, and knowledge of too many people to mention. Despite that, I will give it a try here; for all those who were left out, my apologies!

First and foremost, I would like to thank the Deezmaker 3D Printing crew in Pasadena, California. I learned most of what is captured here by first hanging around their retail shop and later as a member of the team. Deezmaker's President, Diego Porqueras, has been generous in allowing me to use materials that the team developed and that he created personally. (The photos on the cover include a Deezmaker Bukito 3D printer and a gimbal design by Diego). Diego was also a wonderful brainstorming partner when I was wrestling with how to explain some of the concepts. My Deezmaker colleague Rich Cameron (the technical reviewer for this book) was also an invaluable resource, both in his incredibly thorough review of the manuscript and in providing contacts to critical open source community leaders. Deezmaker's Metalnat Hayes provided some of his sculptural 3D-modeling expertise and imparted to me the useful phrase "test case!" to describe things that didn't go well on the first round.

This field would not exist in its current form without the open source community. I am grateful for the support of Kevin Pope and the rest of MatterHackers, who provided early versions of the MatterControl software used in Chapter 8, and for the screen shot on the cover of this book. Marius Kintel, the main developer and maintainer of OpenSCAD software, was gracious in his assistance as well.

Many people granted permission to 3D print their designs or photograph their prints; these are acknowledged where they are used. Many gave good comments and suggestions on ways to present how they were using 3D printing, and I am grateful for the support and permission to display their work.

Thomas MacCalla and Jacqueline Caesar of National University encouraged my early explorations into 3D printing, without which none of the subsequent adventures would have occurred. I also want to thank Nick Agid of Agid Arts and Michael Swartwout of St. Louis University for getting me interested in manufacturing issues, and Salomon Davila of Pasadena City College for providing a perspective on how to encourage students to learn by making things. Mosa, Nancy, and Coco Kaleel and Ethan Etnyre, Karen Mikuni, and Quin Etnyre inadvertently gave me many ideas on how 3D printing and other technologies will affect the future of young inventors.

The Apress production team made this process as painless as writing a book can be. I dealt most directly with Kevin Walter, Michelle Lowman, Anne Marie Walker, Douglas Pundick, Corbin Collins, and Dhaneesh Kumar, but I know they also stand on the shoulders of many giants I did not see.

Finally, I would like to thank all the friends who listened to my frustrations, particularly Margo Kidushim, Paul Orlando, and Lee Schwing. In first place among all of those is my long-suffering husband, Steve Unwin, who has put up with a lot during my pursuit of the perfect 3D print. I thank you all!

—Joan Horvath
Pasadena, California
August 2014

www.it-ebooks.info